Supply chain capabilities for industrial symbiosis

Lessons from the cement industry

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BY
ERNST JOHANNES PROSMAN

DISSERTATION SUBMITTED 2018

AALBORG UNIVERSITY
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CV

Ernst Johannes Prosman is born on the 10th of September 1990 in Middelharnis, The Netherlands. After initially refusing to go to school, he ended up finishing a B.A. in Economics from the Hanze University of Applied Sciences in Groningen in 2011 followed by two master's degrees from the University of Groningen in 2014: a MSc in Supply Chain Management and a Research Master in Operations Management and Operations Research. Again, after initially refusing to do a PhD, he started a PhD at Aalborg University only one year later in 2015 at the Center for Industrial Production. His research on operations and supply chain management in the context of industrial symbiosis is part of the Manufacturing Academy of Denmark (MADE). After handing in, he refuses to work in academia again. But we have seen that before and he might start to miss the academic world after a while.

ENGLISH SUMMARY

In the wake of unprecedented global economic expansion and a quickly increasing middle class, the current economic models jeopardize our future by causing resource depletion, excessive land use and global warming. To address this, concepts such as industrial symbiosis – where waste and byproducts of one industry are used as feedstock for another industry – are gaining traction. However, despite the growing attention and the concept's importance for our future, how to manage supply chain related issues in this context has received rather scarce attention. Yet, the context of industrial symbiosis is rather peculiar due to, for example, the varying quality of waste and byproducts, the cross-industry collaborations and a lack of transparency in the upstream supply chain.

Therefore, to flourish, the context of industrial symbiosis demands the development of new supply chain capabilities. By focusing on the process industry, which on its own accounts for over 70% of all industrial symbiotic activities worldwide, this research provides new insights guided by the following research aim:

To understand the structural supply chain foundations and to develop supply chain capabilities in the context of industrial symbiosis in the process industry

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The presented insights cover the most pressing needs in terms of managing symbiotic supply chains. Building on six studies and one conference abstract, the following supply chain management domains are covered:

- *Sourcing*: a model to select markets with waste and byproducts which fit production requirements.
- *Environmental supply chain management*: a model to assess the environmental impact of the suppliers and link this to the economic performance.
- *Setting up new supplier relationships*: a model on how to create the trust needed to make investments in industrial symbiosis.
- *Managing supplier relationships through supplier integration*: insights into how to design the supplier integration to align the supplier's waste and byproducts with production requirements.

The presented solutions include both mathematical models and organizational capabilities. The novelty lies in the applicability of the solutions as demonstrated by their implementation at a cement manufacturer who is heavily engaged in industrial symbiosis. Lessons from the implementation are presented along with the solutions. By covering a wide range of supply chain activities, this dissertation can serve as a point of departure for supply chain managers.

This dissertation contributes to literature in two broad ways. First, by building on existing knowledge and adjusting this to the context of symbiotic supply chains, new knowledge is developed on supply chain domains who need it the most in the context of industrial symbiosis. Second, as a pioneer in the field of supply chain management in the context of industrial symbiosis, the developed models, propositions and theoretical frameworks serve as avenues for future research.

DANSK RESUME

I kølvandet på en hidtil uset global økonomisk udvikling og en hurtigt voksende middelklasse truer de nuværende økonomiske modeller vores fremtid ved at forårsage ressourceudtømning, overdreven arealanvendelse og global opvarmning. For at imødegå dette, bliver begreber som industriel symbiose - hvor affald og biprodukter fra en industri bruges som råmateriale til en anden industri - centrale. På trods af den voksende opmærksomhed på konceptets betydning for vores fremtid, har der været begrænset fokus på håndtering af forsyningskæde relaterede problemer. Konteksten for industriel symbiose adskiller sig dog væsentligt fra traditionelle supply chains, f.eks. som følge af den varierende kvalitet af affald og biprodukter, tværindustrielle samarbejder og mangel på gennemsigtighed i opstrømsforsyningskæden.

Den succesfulde industrielle symbiose fordrer dermed udviklingen af nye forsyningskædekompetencer. Ved at fokusere på procesindustrien, som i sig selv tegner sig for over 70% af alle industrielle symbiotiske aktiviteter verden over, giver denne forskning nye indsigter styret af følgende forskningsmål:

At forstå det strukturelle grundlag for forsyningskæden og udvikle forsyningskædekapabiliteter i forbindelse med industriel symbiose i procesindustrien

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De præsenterede resultater adresserer centrale elementer af et styringskoncept for symbiotiske forsyningskæder. Baseret på seks studier og et konference abstrakt, adresseres følgende ledelsessystemer til understøttelse af den symbiotiske forsyningskæde:

- *Indkøb*: en model til at identificere markeder med affald og biprodukter, der matcher opstillede produktionskrav.
- *Miljøforsyningskædeforvaltning*: en model til vurdering af leverandørernes miljøpåvirkning koblet til det økonomiske resultat.
- *Opsætning af nye leverandørforhold*: en model for opbygningen af den tillid, der er nødvendig for at investere i industriel symbiose.
- *Håndtering af leverandørforhold gennem leverandørintegration*: indsigt i hvordan leverandørintegration designes for at tilpasse leverandørens affald og biprodukter med de opstillede produktionskrav.

De præsenterede løsninger omfatter både matematiske modeller og organisatoriske kapabiliteter. Nyhedsværdien ligger i anvendeligheden af løsninger, som er demonstreret ved deres implementering hos en cementproducent, der er stærkt engageret i industriel symbiose. Læringen fra implementeringen præsenteres sammen med løsningerne. Ved at dække en bred vifte af forsyningskædens aktiviteter, kan

denne afhandling tjene som udgangspunkt for forsyningskædeledere når de skal løseudfordringer relateret til industriel symbiose.

Endelig bidrager denne afhandling til litteratur på to måder. For det første, ved at bygge videre på eksisterende viden og tilpasse denne til symbiotiske forsyningskæder, udvikles ny viden om forsyningskædes behov i industriel symbiose. For det andet tjener de udviklede modeller, propositioner og teoretiske rammer som veje til fremtidig forskning.

ACKNOWLEDGEMENTS

This thesis is the product of a three-year collaboration with the Manufacturing Academy of Denmark (MADE), Aalborg University and the industrial partner Aalborg Portland A/S. First and foremost, I would like to thank them for offering me the opportunity to learn and to develop myself. Having said this, I consider myself lucky that the rollercoaster called a PhD has been a blast. As a result, this dissertation is a covering essay filled with good memories. Therefore, I would like to express my sincere gratitude to everybody who made this rollercoaster ride so enjoyable.

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Outside work, I would like to thank my friends and family. It is an amazing feeling to be surrounded by such nice persons. I big thank you goes to my parents who raised me with a curious and inquisitive mindset and a love for exploring and challenging knowledge. Last but not least, I would like to thank my host families in Aalborg during the last 10 days of my PhD: Morten & Yana (and the baby), Markus, Michele, Jesper and Romain. I might not have been the most fun guest in those days, but I promise to make it up as soon as I hand in this document. I know I haven’t mentioned all the people but know that the forgotten ones are often the biggest heroes.

Ernst-Jan Prosman
Aalborg, 2018

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CHAPTER 1. INTRODUCTION

Around 1850, the American philosopher Henry David Thoreau wrote in his journal:

> "We pride ourselves on discovering a use for what had previously been regarded as waste, but how partial and accidental our economy compared with Nature's. In Nature, nothing is wasted" (Thoreau 2009, p. 109).

Although written with economic goals in mind, the lessons of Thoreau about using waste as a resource are still relevant and resonate well with the ongoing shift towards sustainable development. Sustainable development has been defined in various ways, but the most commonly cited definition probably comes from the Brundtland Report:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987, p. 41).

Other seminal works added to our current understanding of sustainable development as well. *The Limits to Growth* by Meadows et al. (1972) – a report on a computer simulation about economic growth and population growth constrained by a finite supply of resources – highlighted the limited availability of the earth's resources as an important ingredient of sustainable development. Furthermore, John Elkington, in *Cannibals with Forks: the Triple Bottom Line of 21st Century Business* argued that one has to consider the trade-offs and synergies between what became known as the triple bottom line: economic, environmental and social goals (Elkington, 1997). Sustainable development gained momentum in the last decades, as illustrated by the Millennium Goals and, later, the 17 sustainable development goals of the United Nations[1].

To achieve sustainable development, the concept of a *circular economy* is gaining traction. This is, amongst others, witnessed by the Circular Economy Production Law of the People's Republic of China (The Standing Committee of the National People's Congress China, 2008) and the European Circular Economy package (European Commission, 2015). The current understanding of the circular economy builds on different schools of thought such as *cradle to cradle* (McDonough and Braungart, 2002), *industrial ecology* (Graedel, 1996), *blue economy* (Pauli, 2010), *zero carbon manufacturing* (Ball et al., 2009) and *cleaner production* (Lieder and Rashid, 2016; Ghisellini et al., 2015). The idea of the circular economy is to avoid waste, reintroduce waste as a resource and to preserve the value of products as long as possible. The

[1] The 17 sustainable development goals of the United Nations address issues such as, but not limited to, poverty, education, (gender) equality, clean energy, sustainable cities, pollution and climate change. The United Nations aim to accomplish the goals by 2030 (United Nations, 2015).

concept of Failed Value Exchanges is a pivotal attribute to the circular economy: capturing the economic value that is otherwise destroyed or not internalized from discarded products and materials allows firms to gain a competitive edge in an environmentally preferred way (Yang et al., 2017).

However, in the current economy, industry accounts for a large share of the overall waste generation and, therefore, suffers a high Failed Value Exchange. In the European Union, for example, manufacturing accounts for 10.2% of the waste generation in weight, summing up to over 255 million tons on an annual basis[2] (EuroStat, 2014). Industrial symbiosis – the practice of using waste and byproducts of one firm as input for another firm (Chertow, 2000) – is a well-acknowledged way to reduce waste generation and to limit the Failed Value Exchange (Geng and Doberstein, 2008; Ghisellini et al., 2015).

The process industry plays a major role in industrial symbiosis. Manufacturing processes can be categorized into two general groups: discrete manufacturing and the process industry. Discrete manufacturing typically deals with producing and assembling individual parts, components and finished products. Examples are cell phones, wind turbines, machinery, tools and aircrafts. The process industry, on the other hand, is characterized by processes which include mixing, blending, extrusion, chemical reactions, baking and annealing. The final products range from solids, liquids and powders and are often delivered in bottles, tanks, bags and buckets. Examples of final products of the process industry include cement, paints, fibers, glass and plastic. The MEASTRI Exchanges Database – a comprehensive dataset of symbiotic exchanges composed by The University of Cambridge (Evans et al., 2017) – holds 425 different accounts of industrial symbiosis. A deeper look into the data shows that the process industry is indeed a frequently recurring industry in industrial symbiosis – see figure 1.1 – with an especially important role for the heavy process industry like cement production.

[2] For comparison: this is 24% more waste than the waste generated by households (EuroStat, 2014).

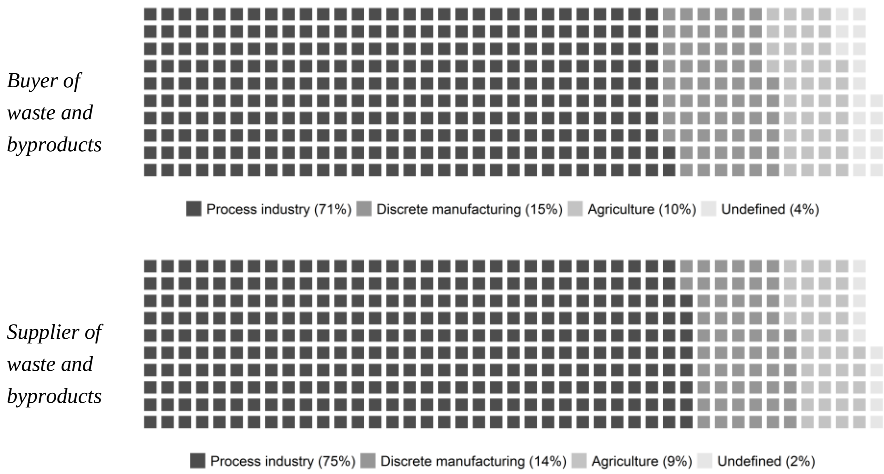


Figure 1.1. Types of industries involved in symbiotic exchanges.

However, despite the heavy engagement of the process industry in industrial symbiosis, much can be gained. In fact, many acknowledge that there is still a large untapped potential for industrial symbiosis in the process industry since many feasible symbiosis opportunities have not materialized – see for instance Yap and Devlin (2017), Chertow and Ehrenfeld (2012), Gibbs and Deutz (2005), Tudor et al. (2007) and Deutz and Gibbs (2008). In fact, although literature abounds in recommendations on how to develop industrial symbiosis, literature does not consider the context of the process industry in their effort to lift industrial symbiosis beyond their current level. Sousa and Voss (2008) stress the importance of contingency factors such as industry for operations and supply chain management endeavors like industrial symbiosis. The next section elaborates on the context of the process industry and how this affects industrial symbiosis.

1.1. INDUSTRIAL SYMBIOSIS IN THE CONTEXT OF THE PROCESS INDUSTRY

Process plants are inherently different from discrete manufacturing plants for the following reasons (King, 2009):

1. **Capital intensive.** Compared to discrete manufacturing, the process industry typically relies on expensive equipment such as ovens, pipelines and cyclones. Those investments often have long pay-back times.
2. **Throughput is limited by equipment.** Whereas in discrete manufacturing firms can often add shifts to increase throughput or to remove a bottleneck,

process plants typically run 24/7 and adding additional labor to, for example, a cement kiln, will not increase throughput with a single iota.

3. **Equipment has limited applications.** Discrete manufacturing often uses equipment such as welding machines, computer numerical control (CNC) machining and lathes which can be used for multiple purposes. In the process industry, equipment is typically optimized for a single purpose such as cement making or paint production.

The above points have implications for industrial symbiosis. Due to the capital intensity, the equipment is often designed and optimized for processing of the existing products and materials (often before the introduction of industrial symbiosis practices). As such, introducing new products such as waste and byproducts to the production system can lead to process inefficiencies such as production losses and unexpected stops as well as implications for final product quality. Due to the 24/7 nature, production losses cannot be compensated by adding overtime. Moreover, the capital intensiveness of the processes often restrains firms from adjusting their processes towards the newly introduced waste and byproducts.

Furthermore, besides the difficulty to change the production setup for the introduction of waste and byproducts, the process industry is limited in dealing with quality issues during the production stage for the following reasons (King, 2009):

1. **Continuous and single direction flow of products throughout the production process.** In discrete manufacturing, parts can often be reintroduced to the production system for additional processing when needed. However, in the process industry, it is often difficult to separate single units or batches during the production stage. Furthermore, products can often not re-enter the production process once they are finished (French and Laforge, 2006). The often limited or non-existing intermediate storage of half-fabricates further complicates reprocessing in case of detected quality issues.
2. **Expensive to start and stop processes.** Stopping the process often comes at large costs in the process industry. Batches might be lost and high cleaning costs (e.g. removing molten plastic which froze in pipelines) and start-up costs (e.g. heating up a cement kiln before production can start) might apply. Hence, production stops caused by waste and byproducts are costly. On the contrary, machines found in discrete manufacturing can often easily start and stop at a low cost.
3. **Input as the origin of quality issues.** A large deal of the variation of quality issues in the process industry stems from the input. The process industry often relies on natural ingredients. For example, chalk for cement, ore for metals, crops for food and pigments for paints. Variation in the purity of the materials (for example due to seasonality or geographic origin of the product) may cause variation in final product quality as well as in process efficiency.

> Waste and byproducts often have lower quality and higher variability (French and Laforge, 2006; Guide et al., 2003; Bansal and Mcknight, 2009), therefore impacting the final product quality.

The difficulty and the costs of dealing with quality issues in processes which are not designed for waste and byproducts, combined with the input as a source for quality issues, puts emphasize on introducing waste and byproducts which fit with the existing production process. Unfortunately, determining the fit of waste and byproducts may be more complicated and time-consuming in the process industry than in discrete manufacturing for the following reasons (King, 2009):

1. **Process as the origin of quality issues.** In discrete manufacturing, worn tooling or improper machine setups typically cause quality issues. Hence, quality issues can often easily be linked to certain production stages. In the process industry, quality issues are often transient due to random variation in for example temperature, pressure, throughput rate and other process parameters.
2. **Detectability of quality issues.** In the process industry, the detection of errors often takes time due to subtle quality parameters. For instance, to assess whether a paint has the correct color, paint must be applied on a test panel and must subsequently be dried before one can assess the conformance with color specifications. Other examples of quality parameters which may take time to detect include viscosity, texture, chemical composition, flavor and aroma. In discrete manufacturing, quality issues are often easier to detect: i.e. spatial dimensions.

Due to the random variation in the processes and the variation in the purity of the input materials, the assessment of how waste and byproducts affect final product quality and process efficiency can become a complex and time-consuming task. Poor detectability and inaccuracies in measurement systems may further complicate the assessment of waste and byproducts. Due to the large variety of factors and potential inaccuracies, data collection might span over a significant time frame (several days up to several months) (Hair et al., 2009) – especially in cases where laboratory tests do not suffice in capturing the full impact and the full impact can only be measured by actually using the waste and byproducts in the production system and reading and analyzing the production data.

In summary, to boost industrial symbiosis in the process industry, the waste and byproducts must align with the current processes. Aligning input with production requirements is typically the domain of supply chain management. Yet, the field of industrial symbiosis has only received limited attention from a supply chain management perspective (Herczeg et al., 2018) even though supply chain management for industrial symbiosis faces different challenges than supply chain management in traditional supply chains (Bansal and McKnight, 2009).

1.2. THESIS OBJECTIVE

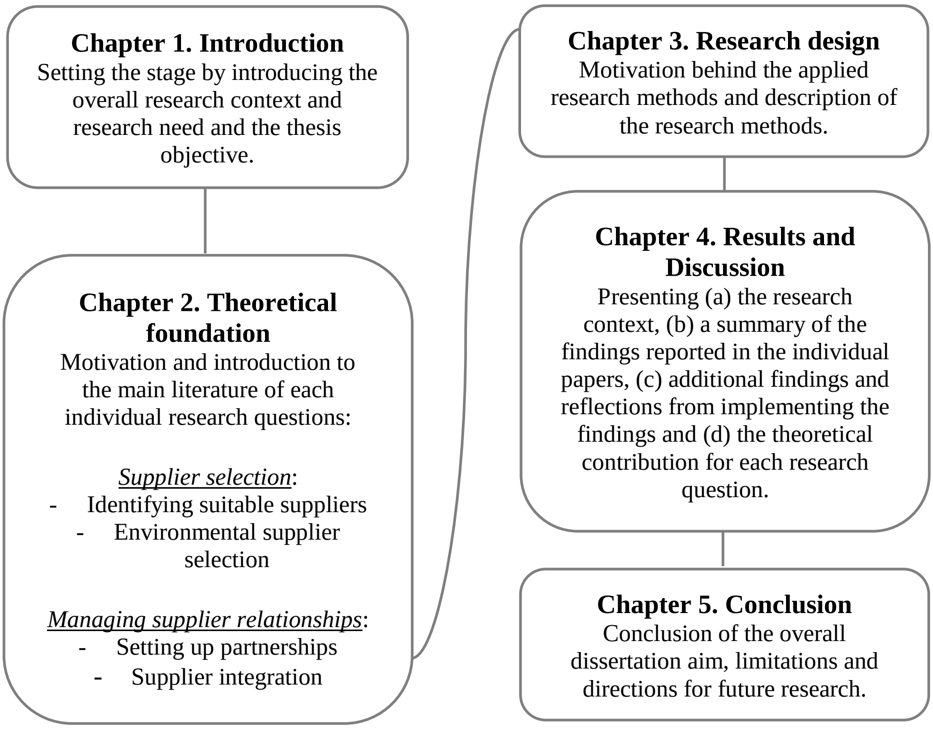
To develop supply chain capabilities for industrial symbiosis in the process industry, one also has to understand the structural supply chain foundations which affect such capabilities. Therefore, this dissertation aims:

To understand the structural supply chain foundations and to develop supply chain capabilities in the context of industrial symbiosis in the process industry

In this dissertation, the term 'structural supply chain foundation' refers to contextual factors which affect supply chain practices. The individual research questions elaborate further on those contextual factors and develop fitting supply chain capabilities. An initial study as part of this research project showed that industrial symbiosis complicates selecting appropriate suppliers and managing the selected suppliers (Prosman et al. 2017) – see paper **I** in the appendix for a more detailed perspective. Hence, this dissertation addresses two overarching themes: 1) supplier selection and 2) managing supplier relationships. Throughout the thesis, the main goal of environmental sustainability is interwoven with the discussed topics.

1.3. STRUCTURE OF THE THESIS

The thesis is divided into five chapters which, together, form a covering essay of the individual papers. The overview of the dissertation is as follows:



CHAPTER 2. THEORETICAL FOUNDATION

This chapter outlines the relevant literature for this research with the aim of ensuring the academic relevance and to position the work. The chapter starts with a general introduction on supply chain literature related to industrial symbiosis followed by literature specific to the research questions related to the overarching themes of 1) supplier selection and 2) managing supplier relationships. This chapter concludes with an overview of the research questions and the contextual factors which influence and justify the research questions.

2.1. SUPPLY CHAIN MANAGEMENT FOR INDUSTRIAL SYMBIOSIS

In the last decades, sustainable supply chain management has enjoyed an immense interest from academics and the number of papers on the topic has ballooned. Table 2.1 provides an overview of the literature reviews on sustainable supply chain management in an attempt to get an overview of the topics covered in literature. Although some aspects of sustainable supply chain management are abundantly covered in literature, literature on supply chains for industrial symbiosis, let alone industrial symbiosis in the process industry, is still rather nascent.

Regardless of the lack of literature on supply chain management for industrial symbiosis (in the process industry), firms who operate in this context may experience context related supply chain issues (Bansal and Mcknight, 2009). In fact, an initial study conducted at the start of this research project showed that industrial symbiosis complicates selecting appropriate suppliers as well as collaborating with the selected suppliers – see paper **I** in the appendix. In addition to the initial study, during the course of the research project, other supply chain challenges related to the context of industrial symbiosis emerged.

In addressing these issues, one has to acknowledge that sustainability often plays a secondary role for firms. Economic performance criteria, in contrast, often play a more prominent role (Sharma 2010; Evans 2017). In operations and supply chain management, five economic performance criteria – cost, quality, speed, dependability and flexibility (Slack and Lewis, 2015) – are often considered important. As such, to lift industrial symbiosis, firms need to overcome or avoid sustainable-economic trade-offs or, most ideally, exploit synergies in sustainable and economic performance. This chase, often referred to as industrial sustainably, is discussed in the next paragraphs for each identified challenge in the context of industrial symbiosis in the process industry.

Table 2.1. Overview of literature reviews on sustainable supply chain management. A wide variety of topics is covered, but not the topic of industrial symbiosis (in the process industry)

Authors	**Topic**
(Fleischmann et al., 1997)	Quantitative models for reverse logistics.
(Govindan et al., 2014)	Reverse logistics and closed-loop supply chains.
(Stindt and Sahamie, 2014)	Closed-loop supply chain management in the process industry.
(Abbasi and Nilsson, 2012)	Challenges to make the linear supply chain more sustainable.
(Gimenez and Tachizawa 2012,)	Extending sustainability to suppliers in the linear supply chain.
(Bekkering et al., 2010)	Overview of the activities in green (bio) gas supply chains.
(Govindan et al., 2015)	Environmental supplier selection criteria.
(Browne et al., 2005)	Life cycle assessments for transport forward supply chains.
(Ashby et al., 2012)	Overview of social and environmental practices in the linear supply chain.
(Srivastava, 2007)	A conceptual framework of sustainable supply chain management activities.
(Carter and Rogers, 2008)	A conceptual framework of sustainable supply chain management activities.
(Seuring and Müller, 2008b)	A conceptual framework of sustainable supply chain management activities.
(Carter and Liane Easton, 2011)	Overview of the progress of research in sustainable supply chain management.
(Fahimnia et al., 2015)	Overview of the progress of research in sustainable supply chain management.
(Reefke and Sundaram, 2017)	Overview of the progress of research in sustainable supply chain management.
(Oliveira et al., 2018)	Overview of the progress of research in sustainable supply chain management.
(Sarkis et al., 2011)	Theoretical backgrounds for sustainable supply chain management.
(Ntabe et al., 2015)	Use of the environmental components of the green supply chain operations reference (GreenSCOR) model.
(Ilgin and Gupta, 2010)	Environmental product design, closed-loop supply chains, remanufacturing and disassembly.
(Pan et al., 2014)	Barriers of waste-to-energy supply chains in terms of finance, technology, institutions and regulation.
(Lin et al., 2014)	Vehicle routing.
(Morgan and Gagnon, 2013)	Remanufacturing scheduling.
(Qaiser et al., 2017)	Sustainable logistics
(Chen et al., 2014)	Sustainable manufacturing network design
(Eskandarpour et al., 2015)	Sustainable supply chain network design.

2.2. SUPPLIER SELECTION FOR INDUSTRIAL SYMBIOSIS IN THE PROCESS INDUSTRY

The next sections present the identified challenges in more detail and, based on relevant literature, present research questions for each identified challenge.

2.2.1. IDENTIFYING SUITABLE SOURCES OF WASTE AND BYPRODUCTS

The initial research suggests that process industries involved in industrial symbiosis may struggle to find suitable sources of waste and byproducts. The struggle arises at least partly from the cross-industry nature of the studied exchange which leads to non-transparent markets (Prosman et al., 2017). In fact, industrial symbiosis typically takes place in a cross-industry nature (Chertow, 2000). The industrial symbiosis in Aalborg Øst, for instance, occurs between the local powerplant, a cement factory, a boiler producer, the local community and some other firms. Other case descriptions of industrial symbiosis also show solely cross-industry waste and byproduct exchanges – see for example the cases of Kwinana and Gladstone in Australia (van Beers et al., 2007), Rotterdam in The Netherlands (Baas and Boons, 2004), Barceloneta in Puerto Rico (Chertow et al., 2008) and the National Industrial Symbiosis Programme in the United Kingdom (Mirata, 2004). The cross-industry nature complicates the ease of finding waste and byproducts which conform with exacting production requirements as firms who are interested in waste and byproducts might be unaware of the quality of such products produced by firms in unrelated industries (Paquin and Howard-Grenville, 2012). This is especially the case when waste and byproducts are sourced from afar and firms tend to know each other less (Prosman et al., 2017). Sourcing from afar is an increasing trend in industrial symbiosis, especially for the waste and byproducts typically used in the process industry such as ashes, slags, sludges and minerals (Jensen et al., 2011; Velenturf and Jensen, 2016).

Furthermore, waste and byproduct exchange platforms which contain relevant information about quality parameters and volume do often not exist. In addition, whereas third party facilitators such as the National Industrial Symbiosis Programme in the United Kingdom can bring firms together and thereby facilitate the sourcing part of industrial symbiosis (Paquin and Howard-Grenville, 2012), such initiatives are not available in many other countries, as such leaving firms to their own devices. Therefore, there is a need to support firms in finding suitable waste and byproducts in different geographical markets.

Case descriptions of waste and byproduct exchanges show that industrial symbiosis in the process industry is centered around waste and byproducts such as ashes, slags, sludges, silica fume, (desulfurized) gypsum, ammonium sulfates, ammonium chloride, caustic soda and minerals (van Beers et al., 2007; Baas and Boons, 2004; Chertow et al., 2008; Mirata, 2004). The geographical origin of the materials from which those waste and byproducts derive may give valuable insights into the quality of the waste and byproducts. Ores from different parts of the world differ chemically and affect waste and byproduct quality stemming from the different ores. Likewise, the quality of fly-ash (a byproduct of coal combustion) is largely determined by the country of origin of the coal. Fly-ash from Russian coal, for example, has a high alkali content[3], which makes it less useful as an additive for the production of certain cement types (but does not restrict other uses such as road filling and concrete structures). Fly-ash from South African coal, on the other hand, has a low alkali content which opens possibilities for replacing virgin materials in low-alkali cement production. The slightly different (chemical) compositions affect the usefulness for the receiving process: small deviations in input can have a large impact in the process industry (King, 2009). Hence, assuring to source high quality waste and byproducts can be of utmost importance in the process industry. As such, a method to derive clues about the country of origin of the product from which the waste and byproducts derive can help firms to locate suitable waste and byproducts and can thereby serve as input for selecting a supply market.

Trade data to the rescue?

Naturally, trade data can help in this pursue. Unfortunately, however, tracing the origin of a product based on trade data can be a complex task due to the high number of transactions, varying quantities and the existence of trade hubs such as major port and besides drawing flow diagrams, methods and models to trace the origin of products is non-existent. Hence, a more systematic approach is needed to support the decision-making process of selecting a supply market. Therefore, the research question becomes:

Research question I: how to identify suitable geographical markets for waste and byproducts?

The solution presented in Chapter 4 builds upon input-output models, an approach developed by Russian Nobel Prize winner Wassily Leontief. Input-output models show interdependencies in economies and are typically used to analyze the economic structure of regions based on material flows between different industries (Leontief, 1951). As shown in Chapter 4, following trade between economies is a very similar task.

[3] Alkali metals contain lithium (Li), sodium (Na), potassium (K), rubidium (Rb), caesium (Cs) and francium (Fr). In fly-ash, high concentrations of sodium and potassium can be found. Those elements are unwanted in the cement chemistry because it increases the risk of 'concrete cancer': an expansive pressure which results in cracks in concrete and loss of strength.

2.2.2. AN ENVIRONMENTAL PERSPECTIVE ON SELECTING SUPPLIERS FOR INDUSTRIAL SYMBIOSIS

Literature and the current perception (of politicians and firms) holds that the circular economy, including industrial symbiosis, has a positive environmental impact (Geissdoerfer et al., 2017). However, research also warns for negative environmental effects, such as not using the most environmental benign material recovery option[4] (Moberg et al., 2005). In fact, industry is often criticized for non-optimal environmental solutions such as waste incineration or down-cycling of materials[5]. Due to their sheer size, process industries often process large amounts of waste and byproducts and may therefore face major environmental pressures, especially in the future. Failing to address these pressures can cause serious reputational damage and, as a result, significant financial loss (Taticchi et al., 2013). It is therefore important to understand the environmental impact of industrial symbiosis in the process industry to prepare firms for this increasing environmental pressure.

However, Wolfenbarger and Phifer (2000) argue that environmental impacts are often complex and ambiguous. Designing the supply chain in an environmental way can therefore become a complicated task (Bai and Sarkis, 2010; Matos and Hall, 2007). The complexity and ambiguity asks for simplified but thoughtful supplier selection criteria (Govindan et al., 2015; Williamson, 2008), especially when one deals with large amounts as in the process industry. As evident from table 2.2., supply chain literature hosts a wide range of supplier selection criteria. However, environmental supplier selection criteria in the context of industrial symbiosis do not yet exist.

[4] In general, in terms of environmental impact, disposal < energy recovery < recycling < reuse < reduction < prevention (Moberg et al., 2005; Schmidt et al., 2007).

[5] Downcycling is when the waste and byproducts are of lower quality or have a lower functionality than the original material.

Table 2.2. Environmental supplier selection criteria. Table adopted and elaborated on from Prosman and Sacchi (2018), based on (Bai and Sarkis, 2010; Freeman and Chen, 2015; Govindan et al., 2015; Handfield et al., 2002; Lu et al., 2007; Zhu and Sarkis, 2004; Xing et al., 2016; Tasca et al., 2015).

Supply chain design aspects	Related attributes
Production processes in the upstream supply chain	Internal recycling at the suppliers; waste water treatment; (solid) waste handling; energy consumption; resource consumption; air pollutants; emission and release of harmful substances.
Product design in the upstream supply chain	Product design for reuse; recycling and recovering of material; green packaging; excess package reduction; toxic and hazardous components.
Environmental management systems in the upstream supply chain	ISO 14001; end-of-pipe control; eco-labeling; continuous monitoring; regulatory compliance; green process planning; up-to-date air; water and pollution permits.
Logistics in the upstream supply chain	Transport mode; distances (in the supply network); fleet efficiency.
Miscellaneous	Management commitment; environmental performance of the supplier's supplier; staff training on environmental issues; ability to improve towards more environmental activities; social responsibility.

An important difference from an environmental perspective between supply chains in the context of industrial symbiosis is the bounded supply. In industrial symbiosis, the supply side of the market is determined by the production of the goods from which the waste and byproducts derive. The amount of fly-ash, for example, is a given depending on the amount of energy produced through coal combustion. An increase in demand for fly-ash will, except for some very extreme cases perhaps, not lead to an increase of coal combustion. In forward supply chains, supply is less bounded. An increase for a given material can often be met by increased production or mining. Figure 2.1 illustrates this difference.

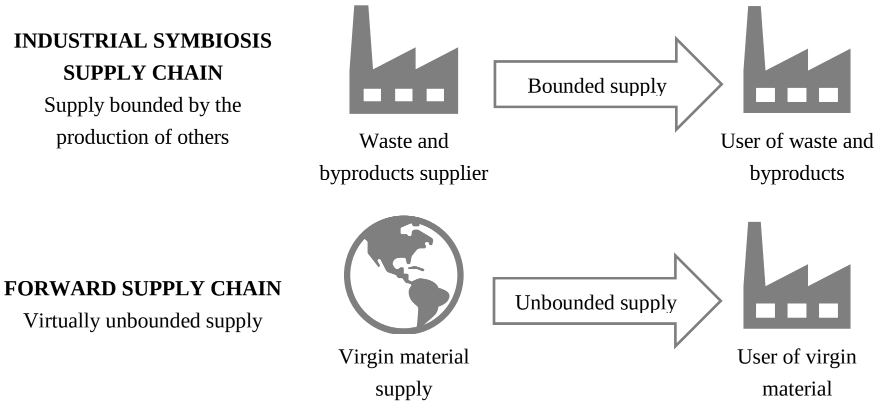


Figure 2.1. Difference between supply chains in the context of industrial symbiosis and forward supply chains.

The bounded supply of waste and byproducts is an important characteristic in designing the supply chain. First, sourcing a product with a bounded supply in a given geographical market might lead to additional transport. As illustrated in figure 2.2, when a firm sources waste and byproducts and thereby creates a shortage on market I, other firms may import waste from another geographical market to overcome the shortage, for example by importing from market II. The additional demand in market II might lead to a shortage of waste and byproducts on this market and waste and byproduct users might import from other geographical markets. This domino effect will continue until firms decide to use virgin materials in response to the shortage of waste and byproducts (scenario A in market III of figure 2.2) or when there is sufficient supply of waste and byproducts to match the additional supply (scenario B in market IV of figure 2.2). In short, sourcing waste and byproducts may induce additional transport depending on the market situation.

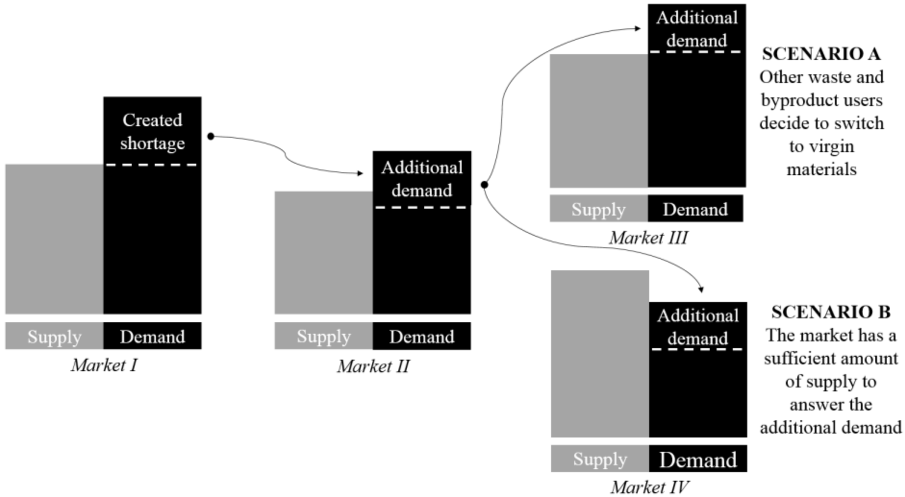


Figure 2.2. Impact of bounded supply on the supply system of waste and byproducts. The arrows represent trade and transport between waste and byproduct markets.

Second, using supply bounded waste and byproducts, avoids the use of the same waste and byproducts elsewhere. When there is sufficient supply of waste and byproducts (scenario B in figure 2.2), disposal may be avoided. However, in scenario A in figure 2.2, firms start to use virgin materials in response to a lack of waste and byproducts. In terms of environmental impact, *disposal < energy recovery < recycling < reuse < reduction < prevention* (Moberg et al., 2005; Schmidt et al., 2007). Therefore, to have a positive environmental impact, firms should not take the waste and byproducts from preferred waste treatment activities. The usage of waste and byproducts in process industries is relatively mature compared to other industries. Currently, there is a shortage of fly-ash due to the extensive use in cement, concrete and road filling and the closure of several coal-fired power stations. Likewise, the availability of waste-based fuels is on the decline due to increased incineration capacity and increased recycling in many countries (EuroStat, 2016). As such, process industries are vulnerable to take waste and byproducts from other firms, thereby not gaining any environmental improvements.

In addition to the above points, the usability of the waste and byproducts may have an environmental impact. The quality of waste and byproducts may differ from supplier to supplier. Ashes and slags, for example, may have different chemistries and waste-based fuels may have different lower heating values and may contain different amounts of hazardous material and inert content. To deal with those materials, additional processing may be needed which may have additional environmental impacts. Moreover, using poor quality waste and byproducts in a capacity constrained process plant may result in lower production output (Prosman et al., 2017). To fulfill the final product demand, either other process plants or additional production lines must compensate for the lost production. In addition, when other plants take over the lost production output, additional transport between the factory and the customer may occur.

The impact of the induced transport, the avoided waste treatment and the usability of the waste and byproducts is not considered in environmental supplier selection criteria. Yet, they might have a major environmental impact on the supply chain level in the context of industrial symbiosis. To prepare process industries who engage in industrial symbiosis for environmental pressure, the research question is:

> *Research question II: which environmental criteria should be considered when selecting suppliers in the context of industrial symbiosis in the process industry?*

Moreover, as firms might not have economic incentives to optimize the supplier selection from an environmental point of view, an additional research question investigates the trade-offs and synergies between the environmental criteria and the economic criteria:

> *Research question III: what are the trade-offs and synergies between environmental and economic performance of supplier selection in the context of industrial symbiosis in the process industry?*

2.3. MANAGING SUPPLIER RELATIONSHIPS IN INDUSTRIAL SYMBIOSIS IN THE PROCESS INDUSTRY

The next sections present literature on managing supplier relationships in relation to the identified challenges of industrial symbiosis in the process industry.

2.3.1. SETTING UP PARTNERSHIPS IN INDUSTRIAL SYMBIOSIS

Trust has been identified as an important ingredient to set-up buyer-supplier relationships in industrial symbiosis (Ehrenfeld and Gertler, 1997; Hiete et al., 2012; Ashton and Bain, 2012). A certain level of trust in the supplier’s ability and integrity is often needed prior to committing to capital-intensive investments in supplier relations (Vanpoucke et al. 2014). In the context of industrial symbiosis, (potential) suppliers might have incentives to misrepresent their ability to get rid of waste and byproducts (e.g. to reduce landfill taxes or to green their environmental profile) (Gulati and Gargiulo, 1999). Moreover, (deliberate) supplier defaults such as late deliveries and poor waste and byproduct quality, may also put the buyer’s investments at risk (Hendricks and Singhal, 2005). Capable and integer suppliers are especially important when supplier specific and capital-intensive investments are at stake (Williamson, 1982).

Case descriptions of industrial symbiosis in the process industry indicate that firms invest in supplier specific and capital intensive waste handling equipment and infrastructure such as pipelines and process changes (Jacobsen, 2006; Zhu et al., 2007).

Although much has been written on trust in the context of supplier specific and capital-intensive investments in supplier relationships (see for example Vanpoucke et al., (2014), and major theories in the field of operations and supply chain management such as Transaction Cost Economics (Williamson, 1982; Zaheer et al., 1998; Nooteboom et al., 1997; Ghoshal and Moran, 1996) and Social Capital Theory (Sako, 1992; Nahapiet and Ghoshal, 1998; Krishnan et al., 2006)[6] have emerged, the role of trust in the context of industrial symbiosis remains unclear. In fact, the context of industrial symbiosis in the process industry has some very specific implications on trust in supplier specific capital-intensive investments. The next section elaborates on this.

Trust in investments in the context of industrial symbiosis

There are two main reasons why the context for trust development in industrial symbiosis differs from the contexts dealt with so far in operations and supply chain management: the cross-industry nature and upfront investments.

First, the cross-industry nature, as discussed in section 2.2.1., may lead to unfamiliarity with the other's business and may, in turn, reduce a firm's insights into the other's integrity and ability (Brinkhoff et al., 2015; Kwon and Suh, 2004; Kwon and Suh, 2005). Second, upfront investments drastically change the way in which trust develops. In contrast with investments in 'normal' buyer-supplier relationships, industrial symbiosis often requires investments before the first delivery can be made. For example, new pipelines need to be in place to transport waste and byproducts and processes must be altered to allow the use of waste and byproducts instead of virgin materials. However, literature on trust holds that trust develops gradually through repeated transactions with the supplier and the embarkment on small joint projects (Dwyer et al., 1987; Gulati, 1995; Li et al., 2008; Ring and van de Ven, 1994; Jap and Anderson, 2007) – a condition which does not apply to initial and upfront industrial symbiosis investments. Although Dwyer et al. (1987) argues that trust can develop quickly, the cases presented in the multiple case study by Vanpoucke et al. (2014) needed between 3 and 15 years of exchanges before the first supplier specific capital-intensive investments were made and another 3 to 10 years before major investments were made.

Since the need for upfront investments complicates the possibility to build up trust based on previous transactions and small joint projects and since the cross-industry

[6] Shortly, Transaction Cost Economics argues that well-justified trust acts as a safeguard against opportunistic behavior. Social Capital Theory holds that trust acts as a relational lubricant.

nature further complicates the development of trust due to limited knowledge about the potential industrial symbiosis partner, the research question is:

Research question IV: how to develop trust in the context of industrial symbiosis in the process industry (where firms come from different industries and have to make upfront capital-intensive supplier specific investments)?

2.3.2. SHAPING THE SUPPLIER INTEGRATION TO IMPROVE WASTE AND BYPRODUCT QUALITY

As mentioned above, the initial research suggests that supplier integration aimed at improving the quality of waste and byproducts in the context of industrial symbiosis in the process industry does not always bear fruit (Prosman et al., 2017).

Supply chain literature often recommends manufacturing firms to support supplier integration with internal integration (Schoenherr and Swink, 2012; Zhao et al., 2011; Das et al., 2006). Following this recommendation, knowledge about waste and byproduct quality requirements travels internally in the buyer's firm from the manufacturing departments to their purchasing functions. The purchasing functions exchange the knowledge with the supplier's sales functions via supplier integration. The supplier's sales department subsequently passes the knowledge about waste and byproduct quality on towards their operations departments (Das et al. 2006). However, although the initial study suggests that this format of supplier integration can lead to improved waste and byproduct quality, the initial study also shows that purchasing and sourcing managers struggle to get waste and byproducts which adhere with high quality standards even when they are supported through internal integration (Prosman et al. 2017).

This is surprising as supply chain literature widely acknowledges that supplier integration (combined with internal integration) leads to improved performance (Tan, 2001; Frohlich and Westbrook, 2001; Schoenherr and Swink, 2012). However, the context of industrial symbiosis in the process industry may require different forms of supplier integration due to potentially high internal manufacturing complexity – i.e. 'the level of detail and dynamic complexity found within the manufacturing facility's products, processing, and planning and control systems' (Bozarth et al., 2009, p. 80).

Internal manufacturing complexity in the process industry might arise from various sources. First, since processes are often interlinked with zero or only limited intermediate storage, it is often difficult to measure at what part of the process quality issues occur (King, 2009). Second, quality and production issues are often transient due to random variation in for example temperature, pressure, throughput rate and other process parameters at each interlinked process step (Van Donk and Van Dam, 1996; King, 2009). As a result, production output and quality can be poor, while, at the end of the day, the root cause remains vague and may consist of a mix or combination of several interrelated causes. The process industry is, therefore, characterized by high internal manufacturing complexity (King, 2009). Figure 2.3 illustrates the high internal manufacturing complexity in the process industry by means of an example.

PROCESS 1 → **PROCESS 2** → **PROCESS 3**

Parameter	*s^2 or σ^2*	*Measurement reliability*
Temp.	Low	High
Liquid velocity	Med.	High
Flavor	Med.	Low
….	….	….

Parameter	*s^2 or σ^2*	*Measurement reliability*
Flavor	Med.	Low
pH value	Low	High
Temp.	Low	High
Emission	High	Low
….	….	….

Parameter	*s^2 or σ^2*	*Measurement reliability*
Flavor	Med.	Low
Viscosity	Low	Med.
….	….	….

Figure 2.3. Example of high internal manufacturing complexity due to measurement issues in interlinked processes without intermediate storage. Some of the measures might only be taken at the end of the process.

Measuring the impact of waste and byproducts on final product quality and production efficiency becomes a complex task due to the high internal manufacturing complexity. Waste and byproducts are often of lower quality than the (virgin) materials they substitute. For example, waste-based alternative fuels may have a lower heating value than fossil fuels and recovered fibers may be weaker than virgin fibers. To enable a supplier to align the quality of the waste and byproducts with the production requirements of the buyer, the supplier benefits from a high understanding of the buyer's processes and products (Bozarth et al., 2009; Setia and Patel, 2013; Zahra and George, 2002). It is therefore important to exchange relevant information through supplier integration activities (Zahra and George, 2002) such as Electronic Data Interchange (EDI) systems, supplier visits and performance evaluations. Previous research shows how the construct of absorptive capacity can offer guidance on shaping effective knowledge exchanges with suppliers – see for example Minbaeva et al. (2003), Lane and Lubatkin (1998) and Nagati and Rebolledo (2012). The next paragraph briefly introduces the construct of absorptive capacity before relating it to industrial symbiosis in the process industry.

Absorptive capacity and the link with industrial symbiosis in the process industry

Absorptive capacity refers to the ability of firms to 'recognize the value of new, external information, assimilate it, and apply it to commercial ends' (Cohen and Levinthal, 1990, p. 129). Zahra and George (2002) identify four complementary dimensions of absorptive capacity. *Potential absorptive capacity* refers to knowledge creation through *acquiring* and *assimilating* relevant knowledge.

Realized absorptive capacity utilizes the created knowledge through *transforming* and *exploiting* the knowledge. Figure 2.4 relates the four dimensions of absorptive capacity to the supplier's capability of improving the quality of waste and byproducts. For a more detailed discussion on absorptive capacity, see Cohen and Levinthal (1990), Zahra and George (2002), Lane and Lubatkin (1998) and Dyer and Singh (1998) or see the theory section of paper **II**.

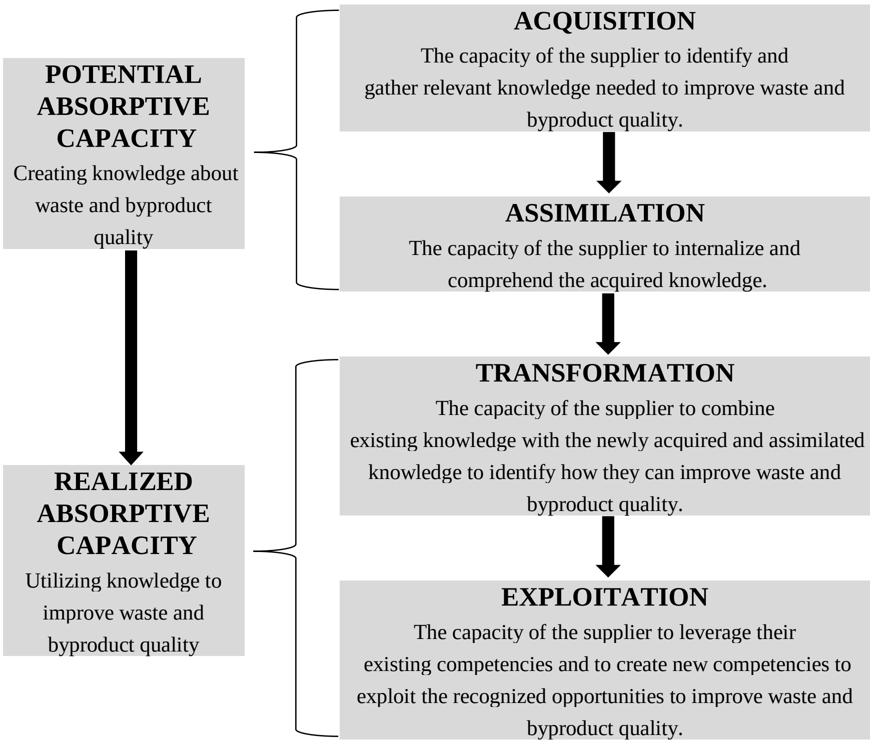


Figure 2.4. The four complementary dimensions of absorptive capacity.

To improve the quality of waste and byproducts for their use in the process industry, firms must deal with high internal manufacturing which restricts the supplier's absorptive capacity. First, at the buyer's side, high internal manufacturing complexity may create ambiguity about what waste and byproduct quality entails. When introducing new material such as waste and byproducts to a production system designed for other (virgin) materials, the impact of those new materials needs to be understood to avoid production loses or quality issues. High internal manufacturing complexity makes it more difficult to understand the impact of the new material on the original output and on the efficiency of the process. Moreover, as production systems may have been running with the same material for years, the impact of the now replaced materials is better understood than the impact of the new materials. Hence, when changing to new materials, the supplier integration which was used for the now replaced materials may result in unclear or incorrect knowledge transmitted to the supplier, as such hampering the first dimension of absorptive capacity: acquisition. Second, from the supplier's side, high internal manufacturing complexity may lead to an insufficient understanding of how waste and byproducts are used by the buyer and how waste and byproducts affect the buyer's performance. The supplier may, therefore, fail to understand the exchanged information or fail to request relevant information, as such incumbering the first two dimensions of potential absorptive capacity.

Fortunately, however, what is perceived as complex by one person may be perceived as less complex by another person (Manuj & Sahin 2011; Campbell 1988; Robinson & Swink 1994; Swink & Robinson Jr 1997). When high internal manufacturing complexity hampers industrial symbiosis in the process industry, firms may benefit from involving persons who consider the complexity as low into the supplier integration. This idea is illustrated in figure 2.5.

		WASTE AND BYPRODUCT SUPPLIER	
		The involved individuals understand the impact of waste and byproducts on the production system	The involved individuals **don't** understand the impact of waste and byproducts on the production system
WASTE AND BYPRODUCT USER	The involved individuals understand the impact of waste and byproducts on the production system	Supplier integration enables suppliers to improve waste and byproduct quality	Supplier integration does not enable the supplier to improve waste and byproduct quality
	The involved individuals **don't** understand the impact of waste and byproducts on the production system	Supplier integration does not enable the supplier to improve waste and byproduct quality	Supplier integration does not enable the supplier to improve waste and byproduct quality

Figure 2.5. Organizing supplier integration in the context of industrial symbiosis in the process industry.

Based on the above insights and motivated by the large untapped potential for increasing waste and byproduct quality through supplier integration, the following research question needs to be further explored:

Research question V: how to organize supplier integration in the context of industrial symbiosis in the process industry?

In line with the above discussion on internal manufacturing complexity and absorptive capacity, in gaining insights into the research question, special attention goes towards the involvement of individuals in the supplier integration.

2.4. OVERVIEW

The above paragraphs present five research questions which will be addressed to answer the overall aim of this dissertation:

To understand the structural supply chain foundations and to develop supply chain capabilities in the context of industrial symbiosis in the process industry

As illustrated in table 2.3, the individual research questions can be divided based on the overarching themes of 1) supplier selection and 2) managing supplier relationships. Moreover, table 2.3 shows the important contextual variables and structural supply chain foundations of industrial symbiosis in the process industry for each research question.

Table 2.3. Overview of research questions and the relation to the context of industrial symbiosis in the process industry.

Theme	**Research question**	**Contextual factors (structural supply chain foundations)**
Supplier selection	*RQ I: How to identify suitable geographical markets for waste and byproducts?*	- Usability of the waste and byproducts - Lack of transparency in the upstream supply chain
	RQ II: Which environmental criteria should be considered when selecting suppliers in the context of industrial symbiosis in the process industry?	- Bounded supply - Usability of the waste and byproducts
	RQ III: What are the trade-offs and synergies between environmental and economic performance of supplier selection in the context of industrial symbiosis in the process industry?	- Bounded supply - Usability of the waste and byproducts
Managing supplier relationships	*RQ IV: How to develop trust in the context of industrial symbiosis in the process industry?*	- Upfront capital-intensive investments - Cross-industry nature
	RQ V: How to organize supplier integration in the context of industrial symbiosis in the process industry?	- Internal manufacturing complexity - Usability of the waste and byproducts - Cross industry nature

However, many supply chain capabilities remain unaddressed, for example logistical strategies, determining stock-levels and supply chain resilience and robustness. However, based on the initial study (Prosman et al. 2017) as well as experiences with student projects towards those topics in real-life situations, these topics are (less / not) influenced by the context of industrial symbiosis in the process industry and the existing supply chain literature already provides sufficient knowledge to address those topics.

CHAPTER 3. RESEARCH DESIGN

To contribute to the overall objective of this dissertation – the understanding of the structural supply chain foundations and the development of supply chain capabilities for industrial symbiosis in the process industry – matters regarding knowledge creation and research design need to be addressed. Multiple research methods are deployed throughout the research project. A major distinction in the research methods comes from the two types of capabilities developed and used in this dissertation, namely:

- *Modelling capabilities (for supplier selection)*
- *Organizational capabilities (for managing supplier relationships)*

The following sections elaborate on this. First, the research philosophy taken in this research will be discussed. From there, this chapter moves on to describe the research methods.

3.1. RESEARCH PHILOSOPHY

Beliefs about how truth can be discovered and how the world works affects the choice of the adopted research methodology. In the broadest sense, two dichotomous positions exist: the positivistic position and the interpretative or hermeneutic position (from the Greek word for interpreter: *hermeneus*).

Loosely put, the positivistic position advocates that observations are context-free and that logical, statistical and mathematical treatment of observations can lead to new knowledge (Hollis, 1994). The interpretative position, on the other hand, holds that actions and phenomena are socially constructed and are impacted by the context in which the action and phenomena takes place. In line with this, the interpretative stance argues that the world cannot be explained by building upon mere observations, as the positivistic view proclaims, but has to be understood from within. Hence, instead of seeking the causes of behavior (e.g. *explaining* why things happen), meaning of action has to be sought (e.g. *understanding* why things happen). Hence, the interpretative position offers a drastically different view on how knowledge should be developed.

In this research, the author *believes* that, between the positivistic and the interpretative position, the positivistic position arguably claims the last word. Neuroscience, for example, points towards how human decisions and emotions can be explained by chemical reactions happening in the brain based on algorithms (Wunderlich et al., 2009). These insights hint toward a deterministic (causal) system in which all human behavior boils down into a series of observable and context-free chemical reactions. By observing these chemical reactions through a positivistic methodology, one can explain why stuff happens: i.e. why humans and firms behave in a certain way. So, theoretically (and science fictionally) speaking, it seems that positivistic research renders interpretative research irrelevant.

However, at the moment of writing, humanity is far from explaining all human behavior, and therefore from explaining firm behavior, by means of (god-like) positivistic research methods. Interpretative research methods, therefore, still have their merits and can yield acceptable causal propositions when positivistic methods fall short; for example, when developing theory about organizational supply chain capabilities which deal with human and firm behavior. The positivistic position, on the other hand, has an obvious link with natural sciences such as physics and chemistry, and has also a lot to offer to mathematics (Hollis, 1994). Hence, positivistic methods can contribute to developing supply chain modelling capabilities (Croom, 2009).

The next sections elaborate on how both positions provide a valuable starting point to address the different sub-questions of this research by linking the positivistic position with the development of modelling capabilities (section 3.1.1.) and linking the interpretative position with the development of organizational capabilities (section 3.1.2.). In addition, section 3.1.3. reflects on how the ontological belief of the research affects the research design.

3.1.1. THE POSITIVISTIC POSITION AND MODELLING CAPABILITIES

The development of modelling capabilities in this research solely relies on context-free observations. Examples of such context-free observations in this study are production capacity (e.g. tons of clinker per hour), energy usage (e.g. kilowatt hour or gigajoules usage), material flows (e.g. tons of waste shipped) and costs (e.g. material prices and production costs).

The Methodology of Positive Economics of Milton Friedman argues that the task of positive research is to:

> "provide a system of generalizations that can be used to make correct predictions about the consequences of any change in circumstances." (Friedman, 1953, p. 4).

The strength of this research therefore depends on the predictive power (judged by comparing predictions with observations) for the phenomena which it intends to explain. The strength or the research does, therefore, not depend on how realistic the assumptions are (Friedman, 1953). This is why, for instance, perfect competition models are still used despite the notion that markets do not consist of perfectly informed and rational buyers and sellers and that products are often not identical. Perfect competition models are used simply because they often outperform the models which rely on more realistic assumptions, i.e. imperfect competition models. Hence, the aim of the developed models in this research is to make accurate predictions, at least to an extend which provides firms with useful insights, rather than basing the models on the most realistic assumptions.

3.1.2. THE INTERPRETATIVE POSITION AND ORGANIZATIONAL CAPABILITIES

When the world we investigate is unlike the natural world, causal explanation may have to make way for a more interpretative understanding. The German philosopher Wilhelm Dilthey wrote that human life can only be understood through understanding the meaning, where meaning holds aspects such as ‘purpose’, ‘value’, ‘development’ and ‘ideal’ (Dilthey, 1985). Likewise, Weber, in his book *Economy and Society*, takes the starting point that humans attach subjective meaning such as emotions, ideas and value propositions to their actions (Weber, 1922). For example, humans might act in a certain way because they expect it to lead to the most effective outcome (e.g. Expected Utility Theory) or because they pursue something so valuable that it overrules all costs and consequences (e.g. self-sacrifice and sheer heroism). As evident from the usefulness of the aforementioned theory, even when one endorses the ideals of positivistic research, acknowledging the merits of interpretative research methods makes a strong case for adopting interpretative research methods when positivistic methods are unattainable.

One area in which positivistic research is often unattainable is the ‘soft’ organizational issues of supply chain management research since it is difficult to separate the context from what is happening (Halldórsson and Aastrup, 2003; Coughlan et al., 2016). In the context of this research, the ‘soft’ organizational issues include amongst other things aspects such as trust, (perceived) complexity and absorptive capacity. In line with this, interpretative methods are employed to develop knowledge about ‘soft’ organizational supply chain capabilities for industrial symbiosis in the process industry. Table 3.1 provides an overview of the philosophical position for each sub-research question.

Table 3.1. Philosophical position for each sub-research question.

Supply chain level	Research question	Type of capability	Philosophical position
All (initial study)	*What are the firm-level challenges of industrial symbiosis in the process industry?*	N/A	Interpretative
Supplier selection	*RQ I: How to identify suitable geographical markets for waste and byproducts?*	Modelling	Positivistic
	RQ II: Which environmental criteria should be considered when selecting suppliers in the context of industrial symbiosis in the process industry?	Modelling	Positivistic
	RQ III: What are the trade-offs and synergies between environmental and economic performance of supplier selection in the context of industrial symbiosis in the process industry?	Modelling	Positivistic
Managing supplier relationships	*RQ IV: How to develop trust in the context of industrial symbiosis in the process industry?*	Organizational	Interpretative
	RQ V: How to organize supplier integration in the context of industrial symbiosis in the process industry?	Organizational	Interpretative

3.1.3. ONTOLOGY

Despite the differences in the positivistic and the interpretative positions, the methodology has some similarities. The similarities arise from naturalistic ontological belief which has been implicitly expressed in the above sections: a ‘top-down’ philosophical belief that “everything arises from natural properties and causes” (Oxford English Dictionary). This naturalistic belief opposes the ontological belief that humans and firms, based on their emotions, values, laws of mind and character-formation, are the foundation which explains how humans, firms and society at large behaves. Wittgenstein exemplifies how one can understand or explain actions from a naturalistic point of view with his famous analogy on chess in *Philosophical Investigations* (Wittgenstein, 1953). The rules of chess determine the purpose of the moves; playing Q-H5 may in the mind of the player be the most effective move to reach the purpose of the game as outlined in the clauses: checkmate. By understanding the rules of chess, one can understand the meaning behind the moves. The same goes for supply chain capabilities. By understanding the ‘rules of the game’ such as the emotions, ideas and value propositions, one can understand the behavior of humans, firms and supply chains. This is in line with Handfield and Melnyk (1998) and Van de Ven (1989), who argue that theories are the cornerstone of knowledge creation in operations and supply chain management. Hence, the supply chain capabilities presented in this research build on theories which intent to describe the rules of the game, thereby aiming to provide good theory which “advances knowledge in a scientific discipline, guides research toward crucial questions, and enlightens the profession of management” (Van de Ven, 1989: p. 486).

Note, however, that the analogy of the chess game can be misleading: the chess analogy suggests that life is bounded to complete and consistent rules which cover all eventualities. Yet, one might play badly on purpose against a beginner or against an easily offended dictator of a banana republic. Hence, in search for understanding supply chains in industrial symbiosis in the process industry and in developing supply chain capabilities to manage such supply chains, extraneous factors should be considered. This is in line with current thinking in supply chain management, where it is argued that no single supply chain capability is optimal in all situations, but that a contingency view is needed (Flynn et al., 2010).

Although much can be said for other ontologies than the naturalistic ones and no clear answer has been reached (Hollis, 1994), this dissertation adopts a naturalistic *belief*. The positivistic, interpretative and naturalistic beliefs together guide the way in which knowledge is build.

3.2. BUILDING KNOWLEDGE

In the attempt to build new knowledge – i.e. supply chain management capabilities for industrial symbiosis in the process industry – the research follows Popper’s four-stage model (Popper, 1999):

1. The problem
2. The attempted solutions
3. The elimination
4. The new problems

According to Popper, problems steer perception: what one sees depends on what one tries to find. For example, how someone studies a watch depends on what the problem is. Whether the problem is to find out what time it is or of what materials the watch is made of, makes a large difference in how to study the watch. Science therefore starts with problems, not with plain observations (Popper, 1999). Likewise, this research as well as the research design is guided by the studied problems. The second stage consists of attempted solutions that solve the problems. It is important to note that the solutions presented in this dissertation are not the only solutions, since one cannot prove this. The elimination of solutions is the third and final stage. Elimination aims to only keep the most effective and efficient solutions[7]. The following paragraphs use the first three steps of Popper's four-stage model to elaborate on how knowledge was created during this research. The fourth step, the new problems, are discussed in *chapter 4: Results and discussion*.

3.2.1. THE PROBLEM

The problems studied in this dissertation are highly affected by the industrial character of this research. The Manufacturing Academy of Denmark (MADE) financed the research through sponsorships by Aalborg Portland A/S. The research context was therefore largely predetermined: sustainable supply chains at Aalborg Portland A/S. A major advantage of the industrial character is that it helps to build the research on existing and practical problems – an important point to conduct relevant research in the field of operations and supply chain management (Coughlan et al., 2016). The starting point for the research questions was a mix of:

1. **Relevance of the project for Aalborg Portland A/S**. The research questions refer to lacking supply chain capabilities at Aalborg Portland A/S to improve their industrial symbiosis activities.
2. **Practicality of the research outcomes**. The research outcomes need to be implementable at Aalborg Portland A/S. In fact, while the implementation of the research outcomes was not part of the research (no action research was conducted), the implementation led to additional insights afterwards. Although not covered in the appended papers, this dissertation will reflect on these insights in *chapter 4: Results and discussion*.
3. **Academic relevance**. The research should address relevant research gaps in the field of supply chain management and industrial symbiosis and contribute to answering the overall research question. The academic relevance is discussed in *chapter 2: Theoretical foundation.*

In order to provide a complete understanding of the industrial problems at Aalborg Portland A/S, the next paragraphs present a detailed case description followed by a summary of the industrial problems.

Case description

Aalborg Portland A/S is a global cement producer with an annual production of 1,525,000 tons of grey cement and 705,000 ton of white cement at their production site in Aalborg, Denmark (Aalborg Portland, 2017). Due to environmental pressure and pursued cost reductions, Aalborg Portland A/S uses large quantities of the following waste and byproducts to produce (especially grey) cement:

[7] Popper exemplifies the second and the third stage by means of an example of a dog which attempts different solutions to get food from his owner. Multiple solutions such as looking sad, barking or standing in front of the food tray might work. However, some attempted solutions by the dog can be eliminated, for example the dog peeing in the corner might not give him the food. Furthermore, of the working solutions, some solutions might work better than others (Popper, 1999).

1. **Sand from dredging.** To maintain the navigational waters at Hals Barre and the Limfjord, sand pumped up by sand dredgers replaces sand which otherwise comes from quarries and the Kattegat.
2. **Desulphurized gypsum.** Gypsum from flue gas desulphurization at Nordjyllandsværket, the local power station, is used as an additive to cement and replaces natural gypsum and anhydrite.
3. **Fly-ash.** Fly-ash from coal-fired power stations replaces aluminum sources such as natural clay or bauxite.
4. **Salt slag.** Salt slag (also known as oxiton) is a byproduct from aluminum production. Salt slag has the same function as fly-ash but requires different processing.
5. **Iron oxide.** Iron oxide (also known as pyrite ash) from the production of sulphuric acid provides a source of iron to produce grey cement.
6. **Alternative fuel.** Alternative fuel is an umbrella term for fuel which substitutes coal and petroleum coke. The alternative fuel consists mainly of the non-recyclable residue fractions of the waste recycling process but also includes meat-and-bone meal.

From the very start of the research project, the project focuses on alternative fuel and, to a lesser extent, on fly-ash. With approximately 235,000 tons of fly-ash and around 140,000 tons of alternative fuel, those two waste and byproducts account for the vast majority of the waste and byproducts used by Aalborg Portland A/S. Moreover, similar materials are also used in other industries such as the heavy energy industry (alternative fuel) and concrete and road construction (fly-ash), thereby rendering those materials particularly relevant.

The industrial problems with academic relevance

An initial study during the first six months at Aalborg Portland A/S, published in the *Journal of Industrial Ecology*, revealed two challenges in the alternative fuel supply chain (Prosman et al. 2017). First, the suppliers of Aalborg Portland A/S struggle to improve the poor quality of the waste and byproducts and Aalborg Portland A/S struggles to support the suppliers in their efforts to improve the waste and byproduct quality. Second, Aalborg Portland A/S struggles to find suitable suppliers as waste markets are non-transparent and platforms with detailed information on waste and byproduct quality and availability do not exist. Hence, the first two research problems deriving from the study in the *Journal of Industrial Ecology* are:

1. *How to identify suitable sources of waste and byproducts?*
    a. *Answered through RQ I*
2. *How to integrate suppliers to improve waste and byproduct quality?*
    a. *Answered through RQ V*

Furthermore, Aalborg Portland A/S imports large amounts of waste and byproducts from countries such as Sweden, the United Kingdom, Finland, Germany, Belgium and

Italy. Due to the sheer environmental impact and due to the always luring environmental criticism, Aalborg Portland A/S aims to pro-actively act on the environmental impact of their industrial symbiotic activities, preferably in an economically viable way. The fourth and fifth research problems therefore are:

3. *How to set-up industrial symbiosis from an environmental perspective.*
    a. *Answered through RQ II*
4. *How to benefit from the synergies of environmental and economic performance?*
    a. *Answered through RQ III*

Finally, during the course of the research project, a final research problem emerged. Aalborg Portland A/S was involved in many new potential industrial symbiosis projects. Yet, many of the potential projects never saw daylight due to investments requirements. Hence the third problem addressed in this research is:

5. *How to set up partnerships in industrial symbiosis?*
    a. *Answered through RQ IV*

3.2.2. ATTEMPTED SOLUTIONS – THE APPLIED RESEARCH METHODS

To find solutions for the above problems, three types of methods were employed. The next paragraphs justify the applied research method for each research question.

Case study

The case study approach is adopted to answer the following questions:

- ***Initial study**: What are the supply chain challenges of industrial symbiosis?*
- ***RQ V**: How to organize supplier integration in the context of industrial symbiosis in the process industry?*

The impact of industrial symbiosis on supply chain management in general and on supplier collaboration in specific was not fully understood prior to the research. A case study design allows to gain a holistic and in-depth understanding of important variables and about the "how's" and the "why's" of the interaction between the variables (Eisenhardt, 1989; Eisenhardt and Graebner, 2007; Yin, 2013; Voss et al., 2002). In addition, high internal manufacturing complexity[8] played an important role in obtaining insights on how to collaborate with suppliers to improve waste and byproduct quality due to the complex impact of waste and byproducts on the production system. The case study design helped to understand the complexity of the

[8] Internal manufacturing complexity is defined as 'the level of detail and dynamic complexity found within the manufacturing facility's products, processing and planning and control systems' (Bozarth et al., 2009, p. 80).

research context (Stuart et al., 2002). For a more detailed account of the case study protocol, see appended papers **I** and **V**.

Models

Models are developed and used to support decision making with regards the following research questions:

- ***RQ I**: How to identify suitable geographical markets for waste and byproducts?*
- ***RQ II:** Which environmental criteria should be considered when selecting suppliers in the context of industrial symbiosis in the process industry?*
- ***RQ III:** What are the trade-offs and synergies between environmental and economic performance of supplier selection in the context of industrial symbiosis in the process industry?*

Mathematical models provide a useful instrument to predict and understand the behavior of complex systems under a range of conditions (Bertrand and Fransoo, 2002). In relation to research question I, the geographical origin of the product from which the waste and byproduct derives often provides a useful indicator of the waste and byproduct quality. For example, in the case of Aalborg Portland A/S, fly-ash quality depends on the origin of the coal; South African coal gives very different fly-ash than Russian coal. Likewise, for alternative fuels, the quality of the fuel depends on the input for recycling and the recycling process itself. *Id est*, do unwanted materials such as chloride or heavy metal containing materials enter the recycling process and is the recycling process capable of separating those unwanted materials? Those factors vary largely between countries based on factors such as the present industries, waste separation at the source and the capability of the recycling firms (often determined by landfill and other environmental taxes) in a country. Hence, developing a mathematical model which traces the origin of materials based on trade data may prove a useful instrument for firms to obtain clues about waste and byproduct quality in different markets. The mathematical model therefore contributes to how to identify suitable sources of waste and byproducts. For details on the model development, see paper **II** in the appendix.

Furthermore, in relation to research question II a mathematical model known as consequential life cycle assessment was employed as a predictive instrument to understand the environmental impact of different industrial symbiotic supply chain setups. Environmental impacts in supply chains are often complex to predict and to understand and decisions such as supplier selection may lead to several (unexpected) environmental impacts. A consequential life cycle assessment is a comprehensive mathematical instrument to predict and quantify the environmental impact in supply chains (Matos and Hall, 2007). Hence, the lessons learned from the consequential life cycle assessment contribute to how to set-up industrial symbiosis from an environmental perspective. For details on the use of the life cycle assessment, please see paper **III** in the appendix.

Finally, research question III builds upon the life cycle assessment used to answer research question II. The life cycle assessment is complimented with an economic assessment. For details on the use of the life cycle assessment and the economic assessment, please see paper **IV** in the appendix.

Conceptual framework based on existing literature

A conceptual study is used to shine light on the following research question:

- ***RQ IV****: How to develop trust in the context of industrial symbiosis in the process industry?*

Much has been written already in literature about how trust develops and how firms can create trust in buyer-supplier relationships. By applying and interpreting the literature on trust to the context of industrial symbiosis (based on academic case descriptions of industrial symbiosis in the process industry), a solid understanding can be built on how firms can develop trust prior to the investments. Combining and integrating different fields of research such as literature on industrial symbiosis and management literature on trust, is an important and relevant method to advance knowledge which has been widely used in other literature streams – e.g. Seuring and Müller (2008b), Herczeg et al. (2018), Angell and Klassen (1999) and Boons et al. (2011). For a more detailed account on the research procedure, see paper **V** in the appendix.

3.3.3. ELIMINATION

An important element of theory and science is falsification, refutability or testability (Popper, 1935). For this, the developed knowledge should contain elements which are potentially possible to prove false. As such, the papers provide testable propositions and clearly measurable constructs.

3.3. DATA COLLECTION

The applied research methods relied on various data sources and often combined quantitative and qualitative data to provide rich insights and to achieve data triangulation (Jick, 1979; Mintzberg, 1979; Yin, 2013). Figure 4.1 provides an overview of the data sources used for the different research methods and research questions. Note, the data collected for the theoretical and conceptual study (research question IV) serves as a sanity check of the developed propositions and the proposed theoretical framework.

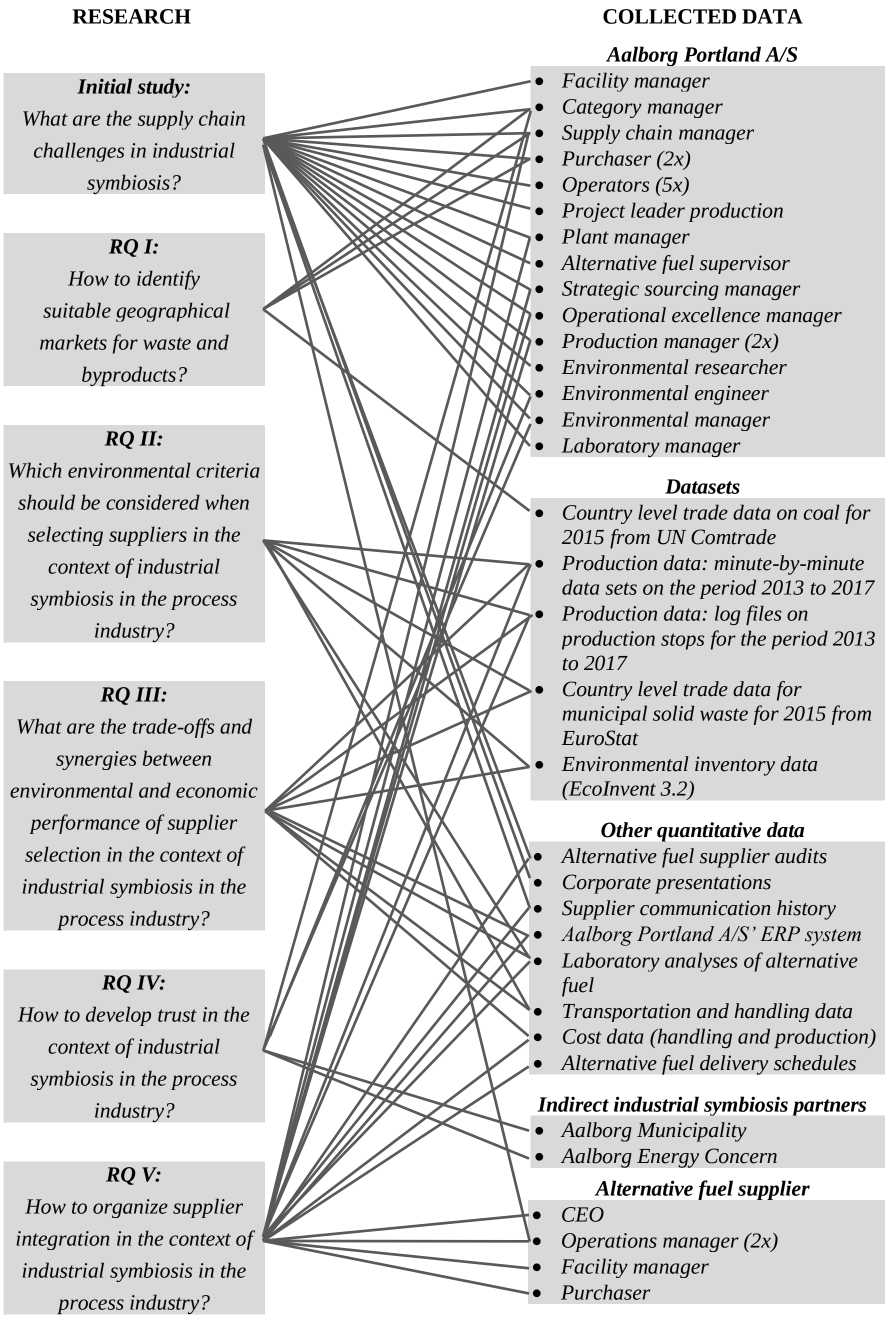


Figure 3.1. Data sources used for the thesis.

Besides this, during the entire research project, the researcher spent two to three days per week at Aalborg Portland A/S. Time was mainly spent in the supply chain department where meetings regarding alternative fuel and fly-ash were frequently attended. Moreover, the researcher participated in countless (coffee) meetings and discussions with basically everyone in the organization to discuss day-to-day issues related (but often not related at all) to the use of waste and byproducts. Furthermore, the researcher spent several days at the control room and the plant to understand the production process and how waste and byproducts affect the production process. In addition, meetings at the laboratory (including conducting quality tests on samples of alternative fuel by the researcher himself) and the research and quality center of Aalborg Portland A/S further cemented the understanding of the cement making process. Finally, several suppliers of alternative fuel where visited during the research project, both for data collection as well as for the implementation of the research findings. Collecting all this surface data allowed the researcher to become ultimately familiar with the cement making process and the context of every research question.

3.4. RESEARCH QUALITY

Several methods where deployed to ensure research quality. Peer-debriefing of data collection, data analysis and results with fellow researchers and employees of Aalborg Portland A/S added to the internal validity and the construct validity of the study. To increase external validity and generalizability, the research builds upon general characteristics, such as Aalborg Portland A/S being a process industry (in this dissertation) or that waste and byproducts are bounded in supply (e.g. paper **III** and **IV**). In addition, data triangulation and the use of NVivo and R for the data analysis increased the reliability and construct validity of the research presented in this dissertation (Yin, 2013). The methodology sections of the individual papers provide more detailed information on how the research quality is ensured.

CHAPTER 4. RESULTS AND DISCUSSION

This chapter presents and discusses the findings of each research question in the same order as in the theoretical foundation – see figure 4.1. Each sub chapter is structured as follows: 1) research context, 2) summary of the findings of the related papers, 3) additional findings and reflections which are not presented in the related papers such as lessons from the implementation and 4) theoretical implications. The aim of the research context is to provide an understanding of the usefulness of the findings as well as to provide insights into the problem which this research tries to solve. The additional findings and reflections provide insights in the usefulness of the solutions and, sometimes, provide new research avenues – thereby discussing the fourth step of Popper's four-stage model: the new problems (Popper, 1999).

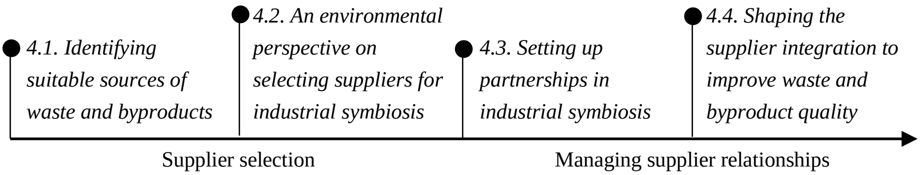


Figure 4.1. Layout of this chapter.

4.1. IDENTIFYING SUITABLE SOURCES OF WASTE AND BYPRODUCTS

The next sections present and discuss the findings related to research question I: *How to identify suitable geographical markets for waste and byproducts?* The findings in this chapter build upon paper **II**.

4.1.1. RESEARCH CONTEXT

Waste and byproducts are becoming an increasingly important ingredient of clinker and cement to reduce the resource consumption and the processing of cement making. The majority of the raw materials of cement consist of limestone or similar rock (around 85%), while other materials are added to reach the correct chemical composition of the cement. The limestone and most other materials are geochemically benign and the mining of those materials does not result in significant problems with acidic or chemically contaminated water (van Oss and Padovani, 2003). Nevertheless, the sheer size of the virgin material extraction[9] prompts environmental pressures from outside such as from (local) authorities and customers. Using waste and byproducts to replace virgin material extraction offers a way out. Furthermore, although materials for cement are abundantly available, they might be quite limitedly available for individual plants (van Oss and Padovani, 2003). It is, therefore, no surprise that the cement industry (and other process industries which use large amounts of materials) uses waste and byproducts in their processes. In addition, the use of certain waste and byproducts such as fly-ash can replace clinker or can result in lower temperatures in the clinker production process, thereby responding to the environmental pressures related to the massive (fossil) fuel consumption of the cement industry (Ekincioglu et al., 2013).

Cement producers often use waste and byproducts such as ground granulated blast furnace slag, burned rice husk ash, kiln dust, burned clays (metakaolin) and silica fume and, as is also the case at Aalborg Portland A/S, iron oxide (pyrite ash), desulfurized gypsum, salt slag (oxiton), bottom ash and fly-ash (van Oss & Padovani 2003). Fly-ash is one of the main byproducts used by Aalborg Portland A/S. Starting around 40 years ago, nowadays Aalborg Portland A/S uses around 235,000 tons of fly-ash per year (Aalborg Portland, 2017b). Opposed to most other cement factories, Aalborg Portland A/S uses the fly-ash as an additive to the raw meal (raw materials), to replace aluminum sources such as clay and bauxite. In fact, the production process is designed for the use of fly-ash, for example with fly-ash storage places, fly-ash feeding systems and a clinker chemistry based on the use of fly-ash. However, high quality fly-ash becomes increasingly difficult to find since power plants in Denmark and the rest of Europe are shifting towards bio-fuel – a fuel which does not deliver the desired quality of fly-ash for the type of cement made by Aalborg Portland A/S. As previous experience learns that fly-ash from bituminous coal from South Africa provides the best quality, new sources of South African fly-ash have to be found. Fly-ash from Russian bituminous coal, on the other hand, delivers the lowest quality of fly-ash.

However, in an effort to identify which European countries[10] use large amounts of South African coal compared to coal from other countries such as Russia, the complexity of international trade formed an obstacle. As evident from figure 4.2, both South Africa and Russia (as well as other nations) are exporting their coal to the European market.

[9] Around 1.7 ton of raw materials (excluding the fuels) is needed for each single ton of cement. In 2016, Aalborg Portland A/S used 3,649,362 tons of chalk, 152,484 tons of sand and 56,557 tons of gypsum to produce 2,256,013 tons of cement (Aalborg Portland, 2017b).

[10] European countries are preferred due to shipping costs

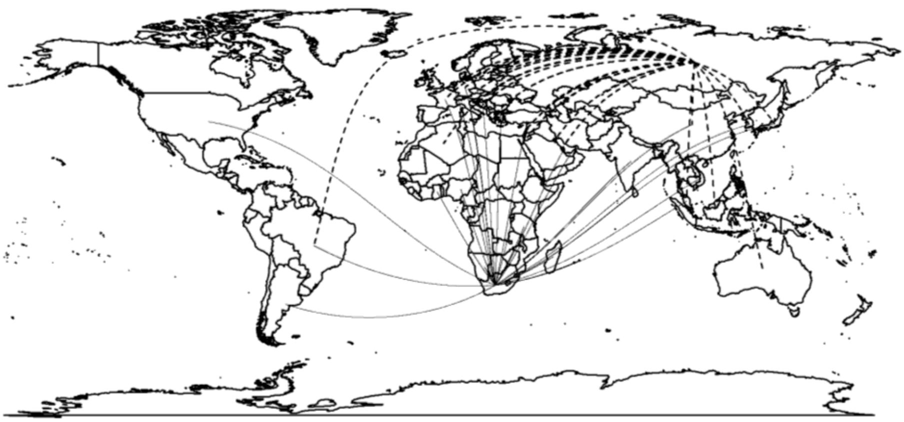


Figure 4.2. Coal export from Russia (dotted line) and South Africa (solid line) to the same European countries complicates finding a country with a high proportion of South African coal (based on data from COMTRADE, 2015).

Furthermore, coal being an internationally traded commodity, the (South African) coal passes major ports such as Rotterdam, Amsterdam, Hamburg and Gdansk where coal is mixed with coal from other countries, see figure 4.3.

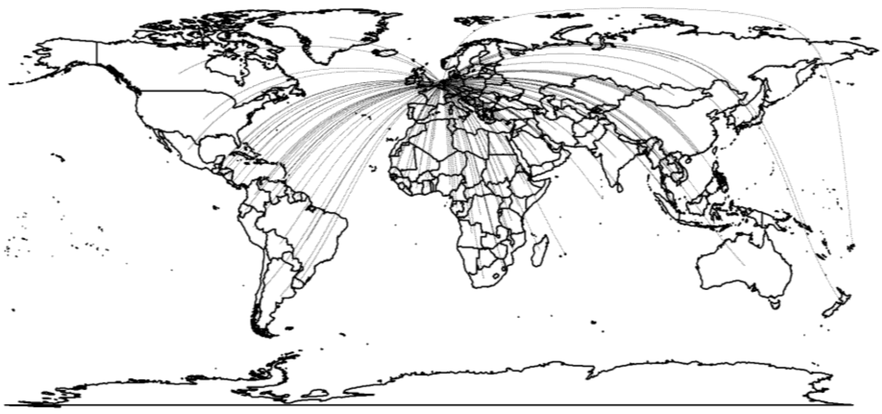


Figure 4.3. The Netherlands imports coal from several countries via the ports of Rotterdam and Amsterdam (based on data from COMTRADE, 2015).

From the terminals, the coal is further distributed by rail and ship to the European hinterland, see for example figure 4.4. The mixing and distribution of coal at hubs such as Rotterdam, Amsterdam and Hamburg results in an even more distorted picture of where South African coal is combusted.

Figure 4.4. Distribution of coal (including South African) from the Netherlands to the European hinterland (based on data from COMTRADE, 2015).

As a result of the trade, Aalborg Portland A/S struggles to identify sources of fly-ash from South African coal. A mathematical model based on trade data was developed which helped to identify countries which use relatively large amounts of South African coal compared to coal from other countries. The next section presents and discusses the model based on paper **II**.

4.1.2. SUMMARY AND DISCUSSION OF PAPER II

The mathematical model builds upon the input-output approach developed by Leontief (1951). For a detailed account on the math behind the input-output model for trade data, please refer to paper **II**.

The next two maps, in figure 4.5 and figure 4.6, show the percentage of South African and Russian coal used on a country level. From the maps, France and Italy seem promising European markets in terms of finding fly-ash from South African coal while not having to deal with fly-ash from Russian coal. The Netherlands, Belgium, Finland and the Baltic states, on the other hand, do not seem such promising markets due to the high percentage of Russian coal present in these markets.

0% 100%

Figure 4.5. Percentage of coal coming from South Africa according to the input-output model. For countries in white, no data is available.

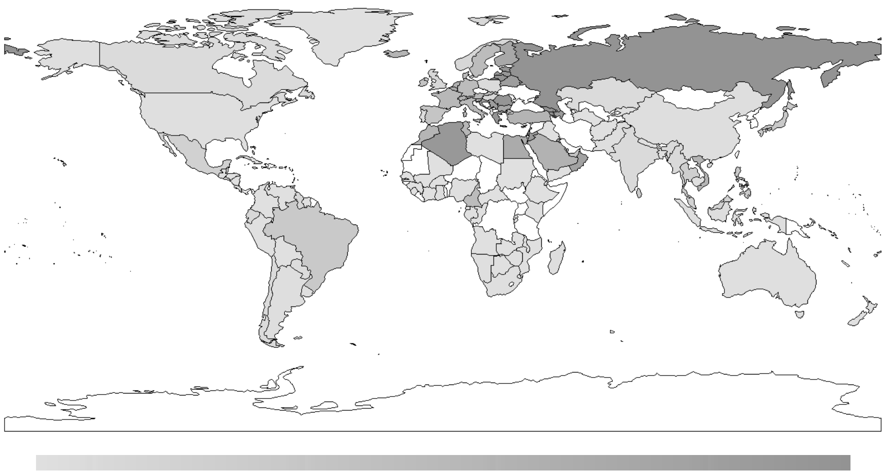


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Figure 4.6. Percentage of coal coming from Russia according to the input-output model. For countries in white, no data is available.

To validate the input-output model, coal-fired power plants in France, Italy, Denmark and Finland were contacted. In line with the outcomes of the input-output model, various coal-fired power plants in France and Italy indeed used South-African coal at least in some periods of the year. In Denmark, some of the powerplants used South-African coal (which is already sourced by Aalborg Portland A/S). No South-African coal and a lot of Russian coal was found in Finland.

Although the model provides useful information regarding fly-ash, the model's assumptions and the model's limitations may render the model less accurate in other circumstances. The discussion section of paper **II** provides a detailed account on the following assumptions and limitations:

- The entire supply network has to be considered.
- A finer granularity of regions may provide more accurate results when countries are large.
- The model is static.
- The model assumes that foreign products fulfil a similar demand as domestically produced products.

4.1.3. ADDITIONAL INSIGHTS AND REFLECTIONS

3 types of additional insights can be glued from the application of the model. First, although the computation time of the model is low, building the model for the first time is time consuming. As long as no ready-made models exist, simply contacting suppliers in different countries can be a faster solution. The model becomes more useful in terms of saving time when there are more potential suppliers, when the suppliers themselves do not know where their input comes from or when ready-made solutions based on the developed model exist.

Second, data availability for the model can be an issue. Although the model is based on easily and freely accessible data, such as the trade data from the United Nations, this data might not be completely up-to-date. A recent check on their website shows that there can be delays of up to 4 years for some of the traded goods and materials. When markets change frequently, relying on a model which is based on outdated data likely provides an incorrect picture of the real world. However, as long as trade is fairly stable, as is the case for coal trade, the model provides useful information.

Third, the model only provides a very first step in locating new suppliers. In the case of Aalborg Portland A/S, coal-fired power plants in France and Italy were contacted following the outcomes of the model. Taking logistical costs in consideration, power plants with access to sea transport were contacted first, see the map in figure 4.7 for locations of power plants in Italy. However, although fly-ash from South-African countries was identified in some power plants located at the sea or major rivers in France and Italy, this did not mean that all fly-ash was available. Other users, such as the concrete industry, were already using the fly-ash.

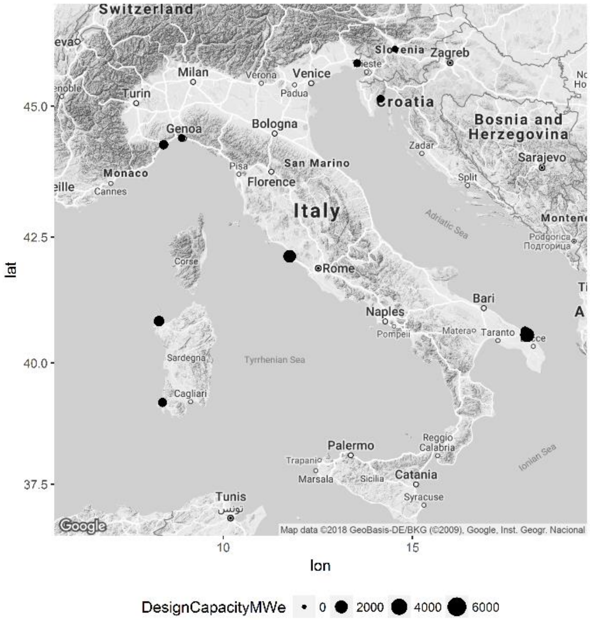

Figure 4.7. Location of coal-fired power plants served as input for contacting power plants along with the input-output model. MWe stands for Megawatt electric, the electric output of a power plant in megawatt.

To improve resource efficiency in the case of fly-ash, firms benefit from coordinating the supply of fly-ash. South African fly-ash often has no added benefits for most concrete types: any fly-ash from bituminous coal has fitting characteristics. As such, whenever Italian coal-fired power plants use South-African bituminous coal, fly-ash is better utilized in cement production; whenever the Italian coal-fired power plants use other types of bituminous coal, fly-ash has a higher utilization in concrete production. As such, a triadic supply coordination can be beneficial. However, although supply chain management literature provides insights into how to manage triads in supply networks – see for example Madhavan et al. (2004); Choi and Wu (2009); Wu et al. (2010) and Wu and Choi (2005) – current literature mainly focusses on *buyer-supplier-supplier* triads[11]. In the context of triads in supply networks of industrial symbiosis, the buyer has to manage the relationship between the supplier and the other buyers, so a *buyer-buyer-supplier* triad. Figure 4.8 illustrates this difference. As literature on buyer-buyer-supplier relationships is scarce, questions

[11] An exception is Bastl et al., (2013) who show that coalition theory is useful in explaining which players in the *buyer-buyer-supplier* triad will from a coalition and with whom, based on the power of the players and their positions in the supply network. However, Bastl et al., (2013) remain rather theoretical and managerial insights lack. For example, Bastl et al., (2013) do not discuss the process of coalition formation. In addition, the assumptions underlying coalition theory hold that firms prefer to form coalitions with similar firms. As firms in industrial symbiosis typically come from different industries, the work of Bastl et al., (2013) may not apply to buyer-buyer-supplier triads in the context of industrial symbiosis.

such as ‘how can a buyer manage buyer-buyer-supplier triads?’ and ‘how do relationships in buyer-buyer-supplier triads evolve?’ remain unanswered and benefit from further research.

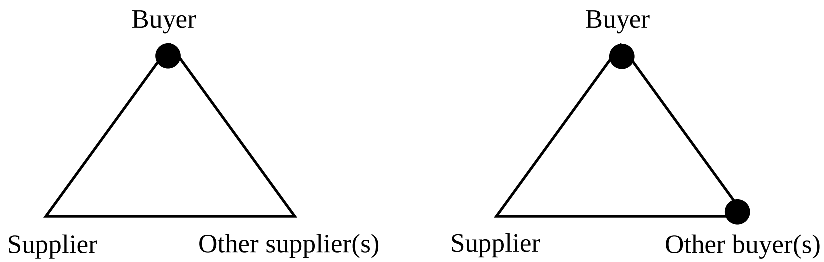

Figure 4.8. Difference between supply chain triads studied in literature (left) and triadic coordination for the use of waste and byproducts (right). Buyers are represented as a circle.

4.1.4. THEORETICAL IMPLICATIONS

Waste and byproducts used in the process industry often have a different quality based on the geographical origin of the material from which the waste and byproducts derive. Literature shows that firms are increasingly sourcing waste and byproducts from afar (Velenturf and Jensen, 2016), but struggle to identify suitable sources (Prosman et al., 2017). A method to identify high quality waste and byproducts in an increasingly global world is especially useful for one of the major players in industrial symbiosis, namely the process industry: quality has often a major impact on final product quality and/or on production efficiency in the process industry (King 2009).

Prior to this research, besides drawing flow diagrams, market selection models which help to locate high quality waste and byproducts in different markets did not exist. The developed model is the first tool presented in literature to locate waste and byproduct markets based on quality and targets the main players of industrial symbiosis: the process industry. The developed model, therefore, makes a useful contribution to research question I:

How to identify suitable geographical markets for waste and byproducts?

However, as evident from the application of the method, the presented method is only part of answering the research question. The identified research questions discussed in 4.1.3. contribute to research by setting an agenda for future research such as how to manage buyer-buyer-supplier triads in the context of industrial symbiosis.

4.2. AN ENVIRONMENTAL PERSPECTIVE ON SELECTING SUPPLIERS FOR INDUSTRIAL SYMBIOSIS

The following sections present and discuss the findings related to research question II: *Which environmental criteria should be considered when selecting suppliers in the context of industrial symbiosis in the process industry?* The material discussed in those sections mainly relies on paper **III**, but is complemented by paper **IV** and conference abstract **I**.

4.2.1. RESEARCH CONTEXT

Cement production has changed significantly over the past few decades. Traditional fuels, such as coal, oil, petroleum coke and natural gas are increasingly making place for alternative fuels. In fact, refuse derived fuel and solid recovered fuel (from now on commonly referred to as alternative fuel), is a common replacement of fossil fuels for cement production in many European countries (Chatziaras et al., 2016). Alternative fuels range from liquid waste fuels (e.g. waste oils, sewage sludge, paint waste, petrochemical waste, lubricants), to solid waste fuels (e.g. mixtures of non-recycled plastics and paper, biomass, car frag, used tires) and to gaseous waste (e.g. landfill gas and pyrolysis gas).

As evident from figure 4.9, Aalborg Portland A/S uses large amounts of alternative fuel. Most of the alternative fuels used by Aalborg Portland A/S consist of the left-overs of recycling and removal of valuable plastics, papers, metals and inert material from municipal solid waste. The left-overs are shredded into small pieces and prepared to become fuel for the cement industry. However, although alternative fuels offer a better option than the traditional fuels in terms of environmental performance (Chatziaras et al., 2016; Ekincioglu et al., 2013), Aalborg Portland A/S still faces environmental pressures which they wish to address.

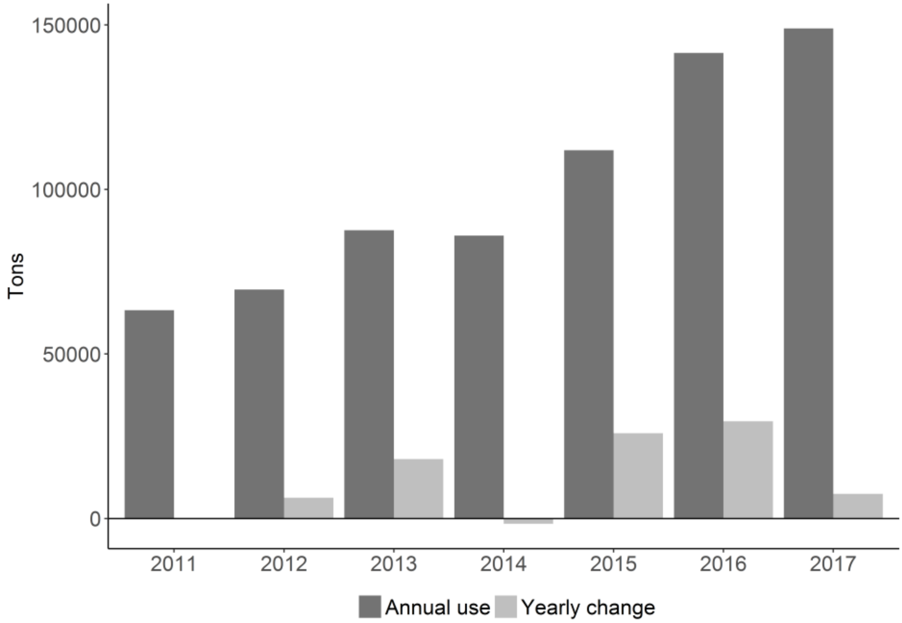

Figure 4.9. Usage of alternative fuel in kiln 87 for grey cement (tons per year).

One way to address the environmental pressure is by optimizing the environmental performance of the entire supply network of alternative fuel, rather than only optimizing the environmental performance at the plant level or even at the supply chain level. However, as shown in the theoretical foundation (section 2.2.2.), supply chains and supply networks for industrial symbiosis differ from forward supply chains and forward supply networks. The next section presents and discusses the findings of paper **III** which reveals environmental supplier selection criteria based on a life cycle assessment and paper **IV** on how to combine economic and environmental performance.

4.2.2. SUMMARY AND DISCUSSION OF PAPER III, PAPER IV AND CONFERENCE ABSTRACT I

The consequential life cycle assessment model presented in paper **III** suggests three main environmental supplier selection criteria next to the environmental supplier selection criteria already presented in literature on forward supply chains (see e.g. Bai and Sarkis (2010), Freeman and Chen (2015), Govindan et al. (2015), Handfield et al. (2002), Lu et al. (2007), Zhu and Sarkis (2004), Xing et al. (2016), Tasca et al. (2015), Spielmann et al. (2007). The suggested supplier selection criteria are:

1. **Indirect transport**: the transport surpassing the transport between the supplier and the buyer of waste and byproducts. When other users of waste

and byproducts fall short of material they may import waste from different markets. This is illustrated in figure 4.10. The environmental impact of the subsequent indirect transport should be considered when assessing the environmental impact of the alternative fuel suppliers.

2. **Affected waste handling activity**: due to the bounded supply of waste and byproducts, other waste handling activities such as recycling and landfilling have less material to process. Mapping the waste trade, as illustrated in figure 4.10, provides insights into which waste handling activity in which country falls short of materials.
3. **Usability**: the quality of waste and byproducts can differ per supplier. The quality deviations result in less efficient production and/or lower cement quality. The negative implications on the production process result in higher emissions per ton of cement during the production stage. Moreover, due to the 24/7 nature of cement making, when lost production results in unfulfilled demand, new production lines or other cement factories cover the lost production. This, obviously, has environmental consequences as well.

*Figure 4.10. Trade of alternative fuel following an increase of demand of one ton on the Swedish market. Swedish waste incineration plants source alternative fuel on the Dutch, Norwegian, United Kingdom's and the German market. Some of these countries source their alternative fuel elsewhere as a response. End-markets do not import any alternative fuel, thereby stopping the chain of trade. Source: paper **III**.*

The affected waste handling activity, indirect transport and usability have a large environmental impact. Direct transport (from the supplier to the buyer), on the other hand, only has a minor impact – see figure 4.11. Yet, direct transport attracts a lot of attention in supply chain management literature, see for example Qaiser et al. (2017). Usability has the largest impact in the case of Aalborg Portland A/S. The large impact of usability stems from the severe impact of alternative fuel on production efficiency. The reduced production capacity results in production and transport of cement from outside Denmark to fulfill domestic demand. Furthermore, also evident from figure 4.11, the alternative fuel suppliers score differently on the three most impactful environmental supplier selection criteria. In fact, none of the suppliers is a top-performer on all criteria. Hence, considering the criteria together is important to make an informed decision.

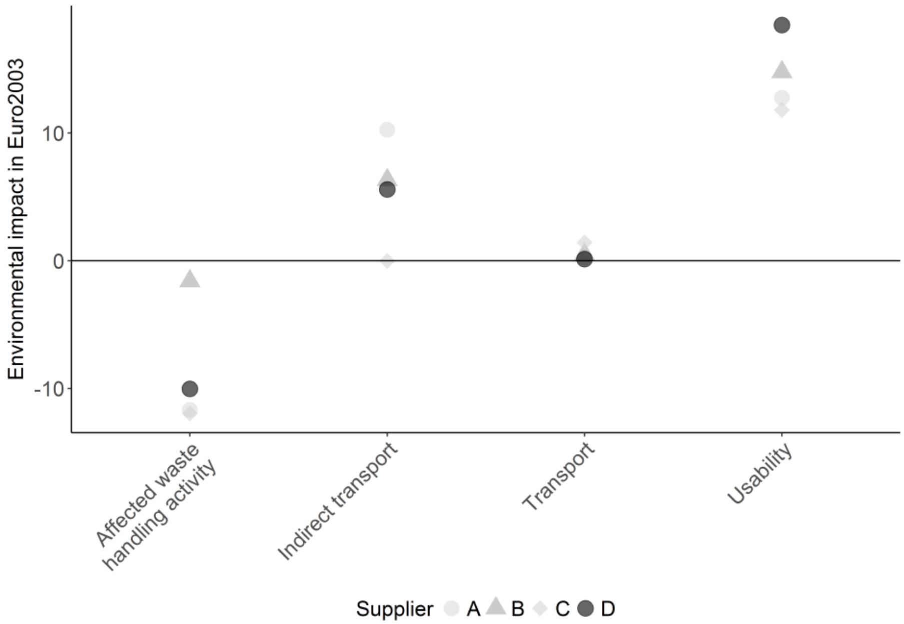

Figure 4.11. The environmental cost of producing one ton of clinker with the alternative fuel offered by the four alternative fuel suppliers under investigation. Environmental impacts are monetized in Euro$_{2003}$ for the sake of comparability. The negative figures for affected waste handling activity are explained by the large share of the alternative fuel coming from the less environmentally benign landfill.

Although the life cycle assessment model provides guidance to select suppliers from an environmental point of view, the assumptions underlying consequential life cycle assessments harm the accuracy of the model. Attention should therefore be paid to defining the goal and scope, defining the system boundaries, defining the product system and the inventory in accordance with ISO 14040:2006 and ISO14044:2006. Still, the accuracy of life cycle assessments remains often an issue (Reap et al. 2008).

Combining environmental and economic performance

To make it attractive for firms to use the abovementioned supplier selection criteria, they should be combined with economic performance. In fact, by combining the life-cycle assessment with a cost comparison of the four suppliers (based on a total cost of ownership approach (Ellram, 1995), several trade-offs and synergies between environmental and economic performance are identified. Figure 4.12 provides an overview of those trade-offs and synergies. Paper **IV** provides a more detailed account on the alignment of economic and environmental performance.

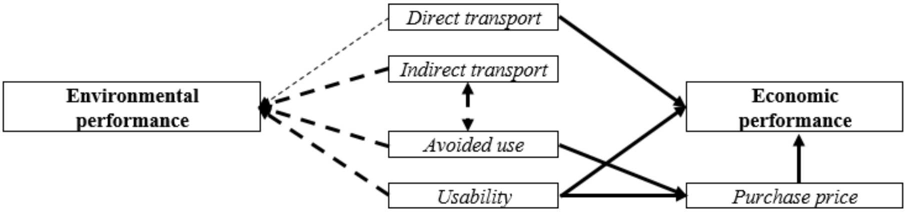

Figure 4.12. Links between environmental and economic performance. The dotted arrows refer to environmental performance; the solid arrows refer to economic performance. The thinner line represents a weak impact.

The links between environmental and economic performance provide insights for firms on how to improve both.

- High usability leads to both environmental and economic performance.
- Waste which comes from landfill leads to economic savings as there are no competitors on the market and the suppliers avoid paying landfill taxes (i.e. a cheaper purchasing price) enabling them to offer a better price. Energy recovery in the cement industry instead of landfilling also leads to environmental benefits.
- Indirect transport is linked to the avoided use: if the avoided use is landfilling, then there will be very limited indirect transport as no other waste handling activities fall short of material.
- Direct transport can account for a large share of the economic costs and is therefore often a target for optimization. However, direct transport often accounts only for a small part of the environmental impact and optimizing direct transport may have a large negative environmental impact due to poor performance on indirect transport, avoided use and usability.

4.2.3. ADDITIONAL INSIGHTS AND REFLECTIONS

Using the outcomes from the consequential life cycle assessment to select suppliers led to additional insights. First, after the latest calciner upgrade in early 2017 (which upgraded the calciner for the use of alternative fuel), the production loss caused by alternative fuel usage was significantly reduced and with it the environmental impact of usability. Hence, the importance of each supplier selection criteria can change after (major) changes in the production line and, as a result, other suppliers may be preferred in terms of economic and environmental performance.

Second, despite the benefits of the consequential life cycle assessment model, data to determine the affected waste handling activity and to estimate the indirect transport might not be available. Conference abstract **I** in the appendix contains a procedure to sidestep the lack of data.

4.2.3. THEORETICAL IMPLICATIONS

Although the environmental impact of alternative fuel in the cement industry is most likely higher than the environmental impact of waste and byproducts in other process industries due to the energy intensiveness of cement making, the identified supplier selection criteria also apply to other process industries[12]. In fact, since the process industry is rather advanced in using waste and byproducts, chances are that using waste and byproducts avoids the use of waste and byproducts elsewhere, thereby also triggering indirect transport. Moreover, the usability of the waste and byproducts can also lead to serious production inefficiencies in other process industries. The production inefficiencies can lead to additional emission or, as is the case for Aalborg Portland A/S, replace production to somewhere else.

Yet, despite the high environmental impact of the industrial symbiosis activities in the process industry, the presented research in paper **III** is the first to provide environmental supplier selection criteria tailored for this context. To assess the environmental impact of selecting suppliers for waste and byproducts in the process industry, the identified supplier selection criteria can serve as input for consequential life cycle assessments or, when the resources for a comprehensive life cycle assessment lack, to serve as guidelines. Therefore, the presented research in paper **III** contributes to research question II:

Which environmental criteria should be considered when selecting suppliers in the context of industrial symbiosis in the process industry?

Furthermore, the research presented in paper **IV** showed how firms can achieve both environmental and economic sustainability. Even though industrial symbiosis has enjoyed an immense interest from academia and the number of papers on how to organize industrial symbiosis has ballooned – see e.g. (Srivastava, 2007; Seuring and Müller, 2008a; Carter and Rogers, 2008; Fahimnia et al., 2015; Govindan et al., 2014; Gimenez and Tachizawa, 2012; Ilgin and Gupta, 2010) – literature does not addresses the alignment of environmental and economic goals through supplier selection in the

[12] In fact, the supplier selection criteria apply to all instances of circular economy and industrial symbiosis. The importance of each supplier selection criteria depends on the context (Prosman and Sacchi, 2018)

context of industrial symbiosis, let alone the context of the process industry and cement production. Therefore, the presented research in paper **IV** contributes to research question III:

What are the trade-offs and synergies between environmental and economic performance of supplier selection in the context of industrial symbiosis in the process industry?

In addition, the procedure presented in conference abstract **I** contributes to literature by outlining the necessary steps to estimate the environmental footprint of their symbiotic supply chain in case ready-made data is lacking.

4.3. SETTING UP PARTNERSHIPS IN INDUSTRIAL SYMBIOSIS

The following sections present and discuss the findings related to research question IV: *How to develop trust in the context of industrial symbiosis in the process industry?* The content of the next sections mainly relies on paper **V**.

4.3.1. RESEARCH CONTEXT

There is a large untapped potential for industrial symbiosis due to never implemented projects (Yap and Devlin, 2017). At Aalborg Portland A/S, many symbiotic projects are proposed. However, although several symbiotic projects got implemented over the years, other proposed symbiotic projects never saw daylight. Not implementing the proposed projects was sometimes caused by the lack of a business case (e.g. extending the excess heat supply to Aalborg Kommune) or due to infeasibility (e.g. recovering the aluminum of packaging in the combustion process). However, many proposed projects never got implemented for no apparent reason. A recent example is the outcome of the collaboration between Aalborg Portland A/S, Aalborg Havn and local recycling firms. During this collaboration, several potential symbiotic opportunities were identified. However, none of these symbiotic opportunities were exploited.

Yet, much time is spent on exploring the business case and the feasibility of the potential symbiosis projects. As such, insights into why some symbiotic exchanges were implemented and others not (at an early stage), as well as insights into how to increase the number of implemented symbiotic exchanges is valuable for Aalborg Portland A/S. Especially since the local government put forward an environmental agenda with a strong focus on industrial symbiosis (Ehrvervssyrelsen, 2013). Discussions within Aalborg Portland A/S, as well as suggestions from literature pointed towards the role of trust (Velenturf, 2015). Major upfront investments are often needed to enable the industrial symbiosis, see for example figure 4.13. Furthermore, Aalborg Portland A/S often did not have business experience with the other firm in the cases in which industrial symbiosis was not implemented. The combination of upfront investments and the lacking business experience may impede trust development and may benefit from trust development strategies tailored for industrial symbiosis.

To fully understand how Aalborg Portland A/S can overcome the trust issue, a conceptual study based on existing literature was carried out. A conceptual study was most appropriate due to the limited access to the cases (because collaboration did not work out and the rate of new proposals is low) as well as the abundant literature of trust in management literature. The next section presents the findings of combining insights on trust development from management literature with the context of industrial symbiosis.

Figure 4.13. Investments in industrial symbiosis by Aalborg Portland A/S: preparation and processing of waste-based fuels.

3.3.2. SUMMARY AND DISCUSSION OF THE TRUST MODEL

The literature review highlighted three different forms of trust as well as three different levels of trust. In terms of the forms of trust, trust can refer to (Mayer et al., 1995; Sako, 1992; Nooteboom, 2002):

- **Trust in the other's ability**: the belief that the other is capable enough to perform the given task.
- **Trust in the other's integrity**: the belief that the other will adhere to the contractual agreements and ethical standards.
- **Trust in the other's benevolence**: the belief that the other will not act in a self-interested way when an opportunity arises.

The three different forms of trust develop through three complementary stages. Ranked from the first to the last stage (Shapiro et al., 1992; Lewicki and Bunker, 1995; Lewicki et al., 2006):

- **Calculus-based trust**: trust based on the estimation of the cost for the other when not acting trust-worthy.
- **Knowledge-based trust**: trust based on knowledge of the other.

- **Identification-based trust**: trust based upon the knowledge that the other is pursuing the same goals and therefore will act in the joint benefit of the relationship.

Normally, firms start to develop trust based on business transactions or by embarking on small joint projects (Vanpoucke et al., 2014). As large upfront investments are needed in the context of industrial symbiosis, other strategies than business transactions and small projects had to be identified to develop trust. By linking the strategies presented in literature with the context of industrial symbiosis, the following strategies seem applicable:

- ***Boundary spanners***: means of gathering knowledge about the other firm. Boundary spanners can be further divided into:
    - ***Firm representatives*** such as supply chain managers, purchasing agents, board-of-director interlocks.
    - ***Third-party facilitators*** such as the National Industrial Symbiosis Programme in the United Kingdom and the Kalundborg Symbiosis Centre in Denmark are common parties in industrial symbiosis (Paquin and Howard-Grenville, 2009).
    - ***Shared network partners*** can include common business partners, governmental bodies such as (local) governments or personal networks such as business clubs. A shared network is considered to contribute to the materialization of industrial symbiosis opportunities (Jacobsen, 2006). Geographical proximity, an often-mentioned enabler in industrial symbiosis literature (Chertow, 2007), can facilitate a shared network.
    - ***Public knowledge*** can include reputation, news items, websites and other forms of publicly available knowledge.
- **Common identity**: shared goals and norms. In the context of industrial symbiosis, social and geographical proximity as well as shared environmental goals can result in a common identity.

Other strategies present in management literature rely on the power of the involved firms or require business transactions[13]. As power is often a given in buyer-supplier relationships, firms cannot proactively apply those strategies when they do not have a power edge over the other. Nevertheless, power can still be a valuable strategy to develop the necessary trust in the needed investments for industrial symbiosis in the process industry.

The framework developed in paper **V** and illustrated in figure 4.14 summarizes how each of the abovementioned trust-developing strategies can contribute to the different levels of trust and the different forms of trust, as such enabling firms to develop

[13] For a more detailed discussion on other trust development strategies, see Ireland and Webb (2007).

sufficient trust levels. For a more detailed discussion of each strategy and the developed framework, please see paper **V** in the appendix.

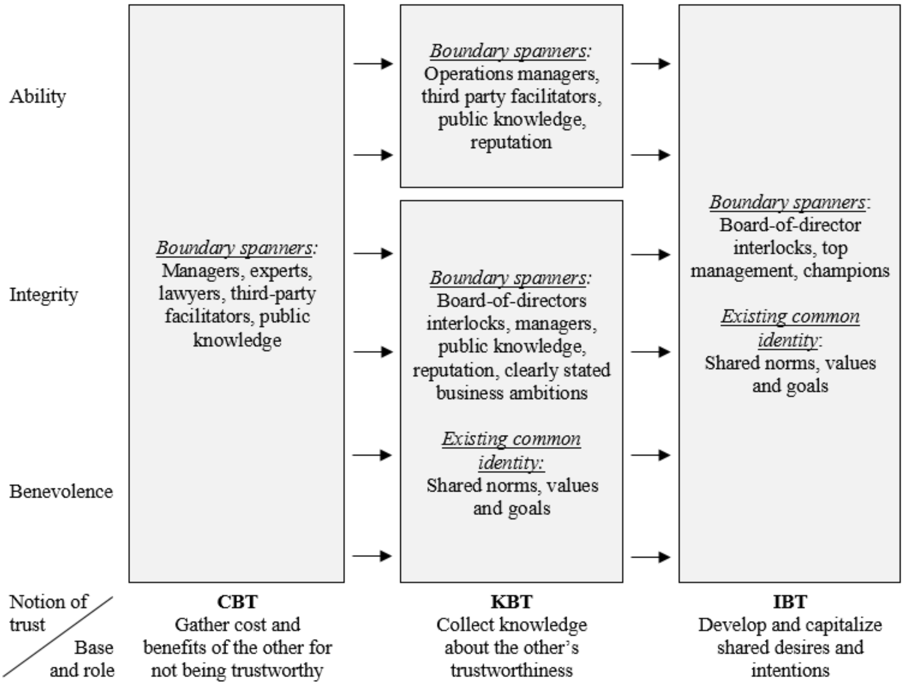

*Figure 4.14. Conceptual framework for developing trust in the context of industrial symbiosis (copied from paper **V**)*

3.3.3. ADDITIONAL INSIGHTS AND REFLECTIONS

As the model was developed in the final stages of the research project, no insights can be derived yet from the implementation of the model.

3.3.4. THEORETICAL IMPLICATIONS

The developed framework is still rather general due to a lack of detailed literature on trust creating strategies in the field of industrial symbiosis. Hence, future research is needed to verify and elaborate on the model. In fact, paper **V** proposes an agenda for future research based on the developed framework. So, the developed framework only offers a very first step in answering research question IV:

How to develop trust in the context of industrial symbiosis in the process industry?

Nevertheless, by providing an initial framework as well as an agenda for future research, the research contributes to the literature on trust in the context of industrial symbiosis (Paquin and Howard-Grenville, 2012; Velenturf and Jensen, 2016; Yap and Devlin, 2017).

4.4. SHAPING THE SUPPLIER INTEGRATION TO IMPROVE WASTE AND BYPRODUCT QUALITY

The next sections present and discuss the findings related to research question V: *How to organize supplier integration in the context of industrial symbiosis in the process industry?* The material discussed in the sections relies on paper **VI**. Insights from implementing the supplier integration as well as daily observations not reported in the paper are presented in the following sections as well.

4.4.1. RESEARCH CONTEXT

As shown in figure 4.9 in section 4.2.1., Aalborg Portland A/S increased the amount of alternative fuel significantly in 2015 and 2016 (the start of the research project). Although the clinker firing process is well suited for alternative fuel, alternative fuel can have a negative impact on the cement output and clinker quality. For example, the large amount of alternative fuel caused kiln stops as a mix of inert material, unburnt but melted plastics and metal and plastic strings clogged the bottom of the calciner. Other problems include lower production output, increased dust emissions due to micro aluminum particles which disrupted the dust filter, high wear and tear on feeders due to metal scrap in the alternative fuel and higher levels of excess air (which reduces production capacity due to limits on the induced draft fan) to reduce CO emissions deriving from incomplete combustion due to peaks in the calorific content. All in all, the alternative fuel had a significant negative impact on the production process and optimizing the alternative fuel can therefore lead to significant cost and environmental reductions. Hence, due to the steep increase of alternative fuel, ensuring the quality of the alternative fuel naturally became an increasingly important objective. To improve alternative fuel quality, the following factors are relevant:

- Higher calorific content.
- Lower moisture content.
- Smaller granularity to ensure complete combustion.
- Lower ash content as the ash might end up in the cement kiln or might clog the bottom of the calciner.
- More homogenous fuel to enhance process optimization. Testing all alternative fuel is too expensive. Hence, using very heterogenous fuel is like driving a car by only looking in the mirrors: the consequences of the alternative fuel on the production process and the cement chemistry are only known afterwards. As such, certain buffers (e.g. a lower alternative fuel feeding rate) might apply in case of heterogenous alternative fuel.

- High biogenic content to lower fossil CO_2 emissions. Lower fossil CO_2 emissions also mean lower environmental taxes.
- Low chlorine content. When chlorine ends up in the clinker, the cement becomes weaker and the risk of corrosion of the steel bars in reinforced concrete is higher. Materials like polyvinyl chloride (PVC) should therefore be used in limited amounts in alternative fuel.
- Limited (heavy) metals which might influence the cement chemistry or affect the electrostatic precipitator (the dust filter).

However, there are some interactions and ambiguities in the list of factors. For instance, a higher chlorine content can be accepted when the calorific content is higher. However, increasing the calorific content can increase the amount of (heavy) metals (for example from carpets and textiles treated with fire-retardants) which can cause problems with the dust filter. Furthermore, whether unburnt pieces of alternative fuel clog the bottom of the calciner depends not only on the ash content, but also on the granularity of the alternative fuel and the composition and shape of the unburnt pieces. Moreover, other factors (possibly affected by alternative fuel) also influence the production process – for instance pressure, induced-fan speed, temperatures, CO, SO_2 excess air, false air and dust). The mix of factors complicates the estimation of the impact of the alternative fuels, as such resulting in high internal manufacturing complexity (Bozarth et al., 2009).

To improve alternative fuel quality in accordance with the above quality requirements, Aalborg Portland A/S engaged in supplier integration with their key alternative fuel suppliers. However, as the initial study pointed out, the supplier integration did not lead to completely improved alternative fuel (Prosman et al., 2017). In fact, the supplier integration with the largest alternative fuel supplier, who is the supplier under investigation in paper **VI**, was not very successful in terms of improving alternative fuel quality. Yet, the supplier under investigation has a large impact on the alternative fuel cost of Aalborg Portland A/S for two reasons. First, the supplier under investigation supplies more than 40% of all alternative fuel of Aalborg Portland A/S. Second, the supplier under investigation was estimated to have the worst impact of all alternative fuel suppliers – see figure 4.15. Besides, many kiln stops are related to the alternative fuel of the supplier under investigation. However, the exact cost of the kiln stops, although significant, is difficult to allocate to a specific alternative fuel supplier and is therefore not taken into account in figure 4.15.

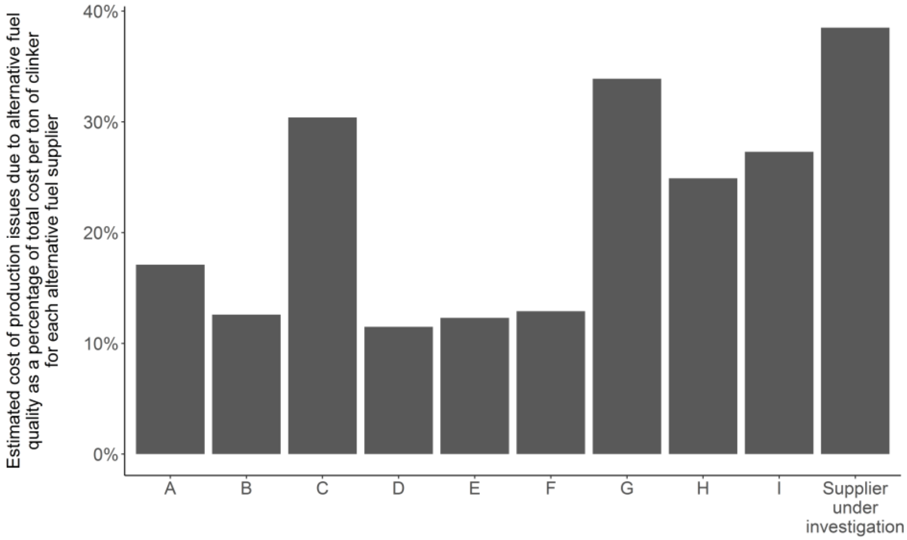

Figure 4.15. Estimated cost of production issues due to alternative fuel quality as a percentage of total cost per ton of clinker for each alternative fuel supplier. The costs of alternative fuel quality include handling cost, CO_2 levies and the cost of lost production. Figures of 2016.

To increase alternative fuel quality, two types of supplier integration were employed. At the offset of the supplier integration, the supplier integration took place between Aalborg Portland A/S' procurement department and the supplier's operations department. The supplier integration took place through phone calls, written correspondence and visits to each other. To provide relevant and correct information to the supplier, Aalborg Portland A/S' procurement department was informed by Aalborg Portland A/S' operations managers about alternative fuel quality and the impact on the production system through internal integration such as weekly meetings, e-mails, internal memos and fuel specifications. As such, the supplier integration (with support of internal integration) had a similar shape as the supplier integration which is widely used elsewhere in Aalborg Portland A/S – for example for other raw materials. In fact, this form of supplier integration supported by internal integration, is in line with widely acknowledged recommendations of supply chain integration literature (Das et al., 2006; Zhao et al., 2011).

However, as the supplier integration did not lead to improved alternative fuel quality, Aalborg Portland A/S' operations managers, with more knowledge about the impact of alternative fuel on the production process, became directly involved in the supplier integration. The supplier integration itself took place in an identical way – i.e. through phone calls, written communication and visits to each other. Also, the intensity of the supplier integration did not change. The next section presents and discusses the findings of the two types of supplier integration.

4.4.2. SUMMARY AND DISCUSSION OF PAPER VI

The results of the longitudinal case study suggest that the supplier integration where the operations managers were directly included led to supplier improvements whereas the supplier integration where the operations managers were only included in the internal integration did not lead to noticeable improvements. When revisiting the theory presented in section 2.2.4., it seems that absorptive capacity plays an important role in the supplier integration in the context of industrial symbiosis and high internal manufacturing complexity. The lacking understanding of Aalborg Portland A/S' procurement department of the impact of the alternative fuel on the production process and their inability of sufficiently mastering this (in the short term) due to a missing technical background, stood at the core of the poor results of the supplier integration as it disabled the supplier to acquire relevant information to improve the alternative fuel quality. However, involving Aalborg Portland A/S's operations managers directly into the supplier integration, opened the possibility for the supplier to learn what was needed to improve the alternative fuel quality. So, the improved information quality increased the absorptive capacity of the supplier. The increased absorptive capacity translated into improved alternative fuel quality. The increased alternative fuel quality is demonstrated in a 1.1% increase in production capacity through the improved fuel alone (a relatively large gain in an already optimized cement kiln). Moreover, kiln downtime related to alternative fuels dropped with 44% after the improvements of alternative fuel quality. In addition, further potential improvements were identified by the supplier but not realized due to a lacking business case. For a more detailed account of the findings and a discussion of the findings in relation to literature on supplier integration and literature on absorptive capacity, please see paper **VI** in the appendix.

4.4.3. ADDITIONAL INSIGHTS AND REFLECTIONS

Although alternative fuel quality improved after the involvement of Aalborg Portland A/S' operations managers, the implementation had a few consequences which have to be taken into account when deciding on how to organize the supplier integration. For example, operations managers may overemphasize operational performance and may therefore aim for 'perfect' alternative fuel quality. As a result, the supplier might face unrealistic requests which might turn out very costly. This is in line with the recommendations of the seminal purchasing book *Purchasing and supply chain management: analysis, planning and practice* by Van Weele (2010), who warns for this effect when involving operations managers in the purchasing process.

Furthermore, operations managers may be unwilling to integrate directly with the suppliers when the impact on the production system is relatively minor or when they feel it is beyond the scope of their job description. For example, at Aalborg Portland A/S, operations managers seem less willing to engage in supplier integration with smaller alternative fuel suppliers. Hence, involving operations managers in every supplier integration where waste and byproducts have a complex impact on the production system may be infeasible.

Finally, improving the alternative fuel is not the only option to optimize the cement output, fuel consumption and clinker quality. Another solution can be process changes, such as upgrading the calciner for alternative fuels – which happened at Aalborg Portland A/S during the main kiln stop in February 2017. The upgraded calciner allowed for a broader range of alternative fuels but the resulting increase of alternative fuel caused other problems in the production process such as high concentrations of chlorine and sulfur in the rotary kiln. Until the next investment round, perhaps a more efficient chlorine bypass, Aalborg Portland A/S therefore has to keep on working with their suppliers to improve alternative fuel quality.

4.4.4. THEORETICAL IMPLICATIONS

Although there exists a large body of supplier integration literature, who to involve in supplier integration remains unclear (Wong et al., 2015). Paper **VI** contributes to literature in the following ways. First, by providing insights into how to organize supplier integration in the context of industrial symbiosis and how to enable the supplier to improve waste and byproduct quality, paper **VI** contributes to the body of literature related to progressing towards cleaner production (Gibbs and Deutz, 2007; Meneghetti and Nardin, 2012). Second, despite the body of literature on absorptive capacity and buyer-supplier relationships in the manufacturing sector (Nagati and Rebolledo, 2012; Rojo et al., 2018; Zhang et al., 2018), contextual factors such as the context of industrial symbiosis, the context of the process industry and internal manufacturing complexity have so far been neglected. This research contributes to literature by including such contextual factors (Lane et al., 2006). In doing so, the presented research in paper **VI**, along with the additional insights presented above offer guidance on research question V:

How to organize supplier integration in the context of industrial symbiosis in the process industry?

CHAPTER 5. CONCLUSION

This chapter concludes this dissertation. The research contribution is summarized and assessed in the light of the overall research aim. Furthermore, the research limitations are presented as well as avenues for future research.

5.1. RESEARCH CONTRIBUTION

The aim of this dissertation was:

To understand the structural supply chain foundations and to develop supply chain capabilities in the context of industrial symbiosis in the process industry

This aim was motivated by the context of industrial symbiosis which is characterized by the bounded supply, the non-transparent supply network, the poor and varying quality of the waste and byproducts and the cross-industry nature. By not understanding these structural supply chain foundations and by not offering fitting supply chain capabilities, literature offers little guidance into how to go beyond the current level of locally based symbiosis activities as often seen in communities such as Kalundborg. The contributions of the individual papers help to break down the walls of the local community by taking a supply chain perspective on industrial symbiosis. Table 5.1 shows the main contributions of the individual papers while reflecting on the usability of the developed supply chain capabilities and the robustness of the research. Taking a supply chain perspective increases the number of potential industrial symbiosis activities thereby increasing resource efficiency. In addition, although the developed supply chain capabilities for industrial symbiosis were developed with the process industry and industrial symbiosis in mind, many supply chain capabilities have a wider application such as other industries and the wider concept of a circular economy. The individual papers in the appendix elaborate on their wider application.

The collective contribution of this dissertation surpasses the sum of individual contributions by providing a wide and detailed view of the challenges and solutions with regards to supply chain management in the context of industrial symbiosis. The challenges and solutions are illustrated and brought to life through the real-life examples given in *chapter 4. Results and discussion*. The broad range of supply chain topics is justified by the pioneering role of this research: as other supply chain research on the context of industrial symbiosis is almost nonexistent, tackling the most pressing challenges along the supply chain is an appropriate first step. The resulting broad perspective helps academics and practitioners alike to understand the challenges and the solutions in this context. Nevertheless, some core topics of supply chain management are intentionally left out of this dissertation (e.g. inventory holding and logistics) because these topics are less affected by the structural supply chain foundations of industrial symbiosis. Already existing literature addresses such issues, for example through inventory models based on uncertain quality (of waste and byproducts) and logistical and supply network design models for reverse supply chains (Chan et al. 2017). Such works should be read together with this dissertation.

Table 5.1. Overview of the developed supply chain capabilities.

Type	Supply chain capability	Usability: ease of implementation and drawbacks	Robustness of the research
Supplier selection	Locating suitable sourcing markets.	Time consuming to build but easy to update with new data. Only a first step in the supplier selection process.	Validity of the model outcomes depends on the fit between the context and the model assumptions.
	Selecting suppliers based on the environmental impact.	Time consuming to build and time consuming to update with new data. Provides also insights in the economic benefits.	Reliability and validity depend on the rigor of the life cycle assessment.
	Combining environmental and economic supplier selection criteria	Fast to implement, but the interactions between the economic and environmental supplier selection criteria and the importance of those interactions can differ based on the context	Based on a single case / single context
Managing supplier relationships	Developing trust for upfront investments.	Some strategies might not be applicable to every situation.	Not tested empirically.
	Improving waste and byproduct quality through supplier integration	Fast to implement but can trigger some resistance in the organization and might lead to sub-optimal situations.	Based on a single case.

In addition, besides the academic contribution through publications in peer-reviewed journals and presentations on international academic conferences, the contribution of this research is also highlighted through other forms of dissemination. For example, Danmarks Radio, the national state broadcasting station of Denmark, published an article of the economic and environmental impact of the research project on their scientific section of the website called ‘Grøn økonomi: affald er en god forretning’ (Green economy: waste is a good business) – see the appendix. Furthermore, the research on the environmental impact attracted political attention as demonstrated by a visit of a prominent national politician to Aalborg Portland A/S to hear more about this research. In addition, parts of the research were presented during MADE seminars which were attended by major industrial players from Denmark.

5.2. LIMITATIONS

This dissertation is not without limitations. First, the problems and the solutions are only studied in one context: the symbiotic activities at Aalborg Portland A/S. To limit the likelihood of contextual biases, the researched challenges and solutions are linked to more universal characteristics prevalent in the context of industrial symbiosis in the process industry. Examples of such characteristics are the low and varying quality of waste and byproducts, the cross-industry nature of the material exchanges and the complexity of using new materials in an already designed and capital-intensive process. However, the prosperous economic context in which Aalborg Portland A/S operates results in high costs of lost production capacity as this directly translates into lost sales. The high cost of lost production paves the way for investing in higher quality waste and byproducts to reduce production losses. In less prosperous times, the need for such activities is limited due to a sufficient production capacity. Furthermore, the Danish culture, with decentralized organizational structures, might limit the insights on how to manage supplier integration. These insights should therefore be treated with extra care outside of this context.

A second limitation is the role of the researcher. The researcher was actively engaged in the daily processes of the supply chain department of Aalborg Portland A/S, potentially leading to an insider's bias: being blindsided for the issues and conflicts related to the proposed solutions outside the supply chain department. Through active engagement with other departments such as the production and environmental department, and data triangulation through collecting data from multiple sources, this research tried to limit the potential of an insider's bias.

Finally, a major limitation relates to the insights from the implementation and evaluation of the solutions. These insights by no means pretend to resemble any scientific results. Rather, the insights of the implementation phase are based on impressions of the researcher and other employees of Aalborg Portland A/S. Nevertheless, by gathering multiple impressions, the insights from the implementation phase gives initial insights into the usability of the solutions and may pave the way for the identification of new research avenues. Nevertheless, those insights should be treated with care. For the limitations of the individual papers, for example related to the type of study, please refer to the papers attached in the appendix.

5.3. FUTURE RESEARCH

As evident from table 5.1, future research should address the usability and the robustness of the research. This can both involve the refining of the proposed supply chain capabilities as well as proposing other capabilities which are more useful for solving the challenges for supplier selection and supplier relationship management in the context of industrial symbiosis in the process industry. In addition, other supply chain challenges (than the ones addressed in this research) may emerge in the context of industrial symbiosis in the process industry. Future research should first identify such issues and subsequently propose and test supply chain capabilities to address those issues. So, to conclude this never-ending tale called research, the presented research provides a useful avenue for both future research and practice while providing acceptable insights for both practice and academia for the time being.

CHAPTER 6. LITERATURE LIST

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APPENDICES

Paper I. Prosman, E.J., Wæhrens, B.V. and Liotta, G. (2017), “Closing global material loops. Initial insights into firm-level challenges”, *Journal of Industrial Ecology*, Vol. 21, No. 3, pp. 641.650.

Paper II. Prosman, E.J. and Wæhrens, B.V. (2018), “Tracing the origin in commodity supply networks: an input-output approach based on trade data”, submitted for first round of review at the *International Journal of Production Economics*. The paper is presented at the 5th EurOMA sustainability forum.

Paper III. Prosman, E.J. and Sacchi, R. (2018), “New environmental supplier selection criteria for circular supply chains: lessons from a consequential LCA study on waste recovery”, *Journal of Cleaner Production*, Vol. 172, pp. 641-650.

Paper IV. Prosman, E.J. (2018), “A framework for environmental and economic supplier selection in industrial symbiosis. Insights from the cement industry”, *course paper*.

Paper V. Prosman, E.J., Ramsheva, Y. and Wæhrens, B.V. (2018), “Dare to make investments in industrial symbiosis? A conceptual framework and research agenda for developing trust”, submitted for first round of review at the *Journal of Cleaner Production*. The paper is presented on the 25th EurOMA conference.

Paper VI. Prosman, E.J. and Wæhrens, B.V. (2018), “Improving waste quality in industrial symbiosis: insights on how to organize supplier integration”, submitted for first round of review at the *Journal of Cleaner Production*. The paper was presented on the 25th EurOMA conference.

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PAPER I

Prosman, E.J., Wæhrens, B.V. and Liotta, G. (2017), “Closing global material loops. Initial insights into firm-level challenges”, *Journal of Industrial Ecology*, Vol. 21, No. 3, pp. 641-650.

Closing Global Material Loops

Initial Insights into Firm-Level Challenges

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Circular economy
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Summary

Sharing and exchanging waste materials between industrial actors, a practice known as industrial symbiosis (IS), has been identified as a key strategy for closing material loops. This article adopts a critical view on geographical proximity and external coordinators—two key enablers of IS. By "uncovering" a case where both enablers are absent, this study seeks to explore firm-level challenges of IS. We adopt an exploratory case-study approach at a cement manufacturer who engages in cross-border IS without the support of external coordinators. Our research presents insights into two key areas of IS: (1) setting up the initial IS exchange and (2) improving the performance of existing IS exchanges. Moreover, our research provides initial insights into the underlying nature of the related firm-level challenges and explores how internal coordination between manufacturing and purchasing may or may not act as a substitute for geographical proximity and external coordinators. In doing so, our insights into firm-level challenges of long-distance IS exchanges contribute to closing global material loops by increasing the number of potential circular pathways

Introduction

Circular economies form a prime element of today's environmental and political agenda and industrial symbiosis (IS) plays a pivotal role herein (Geng and Doberstein 2008; Ghisellini et al. 2015). IS refers to the practice of using waste and by-products of one firm as feedstock for the other with the underlying aim of economically reducing their aggregate environmental impacts (Chertow 2000). Studies toward the factors catalyzing IS stress the importance of *external coordinators (third parties dedicated to facilitating IS exchanges)* and *geographic proximity (limited to a regional level)* (Boons and Spekkink 2012; Walls and Paquin 2015). Both geographic proximity and external coordinators connect firms and help shape the IS exchange (Paquin and Howard-Grenville 2012). To the best of our knowledge, all IS cases described in literature stage at least one of those two factors, exemplifying their importance (see for example van Beers et al. 2007; Yu et al. 2014; Costa and Ferrão 2010; Jacobsen 2006; Zhu et al. 2007). Yet, recent trends show an increase in long-distance IS exchanges (Jensen et al. 2011; Velenturf and Jensen 2015), sometimes even crossing borders (Velenturf 2015). However, despite the call of practitioners, little research addresses whether, how, and what questions in relation to developing long distance IS exchanges without the support of, often locally operating, external coordinators (Walls and Paquin 2015). This article tries to fill this void by extending prior IS research as we 'uncover' and explore the firm-level challenges in such a context.

The prospects of long-distance IS exchanges without the support of external coordinators are enchanting from both a circular economy and economic perspective. First, the supply and demand of waste is often geographically dispersed (Sterr and Ott 2004) and very few firms consider waste exchanges as an important factor to relocate. Moreover, many planned eco-industrial parks have failed (Chertow 2000; Heeres et al. 2004). So, enhancing a firm's capabilities to engage in long-distance IS exchanges increases the number of circular pathways and, therefore, the likelihood of firms closing material loops (Sterr and Ott 2004). Furthermore, research by Jensen et al. (2011) suggests that the environmental savings of resource reuse often outweigh the environmental impacts of the increased transport. Second, stretching geographical limits may allow firms to partner with multiple suppliers delivering the same type of waste. This not only reduces the firms' vulnerability for IS supply chain disruptions (Zhu and Ruth 2013) but also raises the volume of reused materials, as such making investments in IS related processes more appealing due to scale. As only a few external coordinators cover large distances, ensuing insights from our explorative research contributes to IS and, as such, to the development of circular economies.

Based on an in-depth case study at a cement plant, our initial insights extend well-established understandings on how IS develops and becomes more embedded. Moreover, insights into the role of *internal* coordination in dealing with the related firm-level challenges equips firms who participate in IS and provides research avenues for future work. In addition, external coordinators can use the insights of our study to improve their services.

Literature Review

Literature holds various attitudes toward IS. For example, a widely used definition defines IS as the use of waste and by-products of one firm as feedstock in another, otherwise unrelated, firm (Chertow 2000). However, the notion of 'unrelatedness' in this definition raises multiple issues as it implies, among other things, a temporal dimension; the cement industry engages in IS longer than 30 years, so when is it still 'unrelated' (Lombardi and Laybourn (2012)? As redefining the meaning of IS goes beyond the scope of our research, we refer to Lombardi and Laybourn (2012) for a more detailed critique on the notion of 'unrelatedness'. Nevertheless, in line with Lombardi and Laybourn (2012), in this research we relax the notion of 'unrelatedness'. As such, we adopt a more recent understanding of IS, in which IS entails exchanges of otherwise discarded materials (Chertow and Ehrenfeld 2012). According to this view, IS comprises a wide range of waste handling practices including the reuse of materials such as fly ash (see Jacobsen 2006) and the use of steam from waste combustion (see Behera et al. 2012 and Park and Park 2014).

Despite the different perceptions of IS, literature argues that IS benefits from 'the synergistic possibilities offered by *geographic proximity*' (Chertow 2000, p.314, emphasis added). Furthermore, research highlights the important role of *external coordinators* for developing IS (Costa and Ferrão 2010; Paquin and Howard-Grenville 2012). In the remainder of this literature review we will first describe the role of geographic proximity and external coordinators in IS. We then argue why and how *internal* coordination may fulfill the role of both geographic proximity and external coordinators.

The role of geographic proximity and external coordinators

IS exchanges do often not connect to the buyer's and supplier's core competences and IS partners often come from different industries (Bansal and Mcknight 2009; Zhu and Ruth 2013). This results in both social and cognitive distances (Boschma 2005). Yet, due to the complexity of IS – resulting from required investments and new ways of working (Mirata 2004; Zhu and Ruth 2013) – firms likely benefit from social and cognitive proximity (Boschma 2005).

Social proximity describes the degree of social embeddedness of relationships – friendship, kinship and experience – where the arising trust facilitates tacit knowledge exchanges (Uzzi 1997). Cognitive proximity refers to the firm's absorptive capacity to identify, interpret and use new knowledge (Boschma 2005). A lack of cognitive proximity may create unawareness of (potentially) occurring problems and their related solutions (Robertson and Langlois 1995).

Geographic proximity and external coordinators play a pivotal role in developing IS (Mirata 2004; Sterr and Ott 2004). We use Boschma's (2005) definition of geographic proximity as 'the spatial distance between actors, both in an absolute and relative meaning' (p. 63) to account for different perceptions of distance, for example between the USA and The Netherlands. In IS, geographic proximity often implies within the same eco-industrial park (for example Ulsan, South Korea (Behera et al. 2012) and Kwinana and Gladstone, Australia (van Beers et al. 2007)). We define external coordinators as third parties who facilitate IS between firms. Well-known examples of external coordinators include the National Industrial Symbiosis Programme (NISP) in the UK and the Kalundborg Institute in Denmark.

Both geographic proximity and external coordinators enhance social and cognitive proximity. First, geographic proximity assists in developing social ties (social proximity) between firms (Sterr and Ott 2004; Zhu et al. 2015; Paquin and Howard-Grenville 2012). Moreover, geographic proximity facilitates one-on-one meetings and site visits – hence, helping firms to identify potential and beneficial IS exchanges and to create a common understanding of IS issues (cognitive proximity) (Sterr and Ott 2004; Zhu et al. 2015). For example, in the small community of the frequently cited Kalundborg symbiosis, employees of different firms knew and trusted one another prior to IS exchanges (Ehrenfeld and Gertler 1997). Second, external coordinators fulfill a similar role by connecting industries and key persons (social proximity) (Boons and Spekkink 2012; Paquin and Howard-Grenville 2012), emboldening knowledge transfers (cognitive proximity) (Panyathanakun et al. 2013), encouraging cooperation (Golev et al. 2015) and reassuring the commitment of parties (social proximity) (Mirata and Emtairah 2005). In addition, both geographic proximity and external coordinators may support IS development by expressing environmental norms to combat economic motives which may otherwise impede IS (Chertow and Ehrenfeld 2012).

Nevertheless, although both geographic proximity and external coordinators play a prime role in IS, throughout the remainder of the literature review we argue that, based on IS and supply chain literature, the presence of neither proximity nor coordinators is required for IS. The absence of both factors asks for new ways of coordination (Mattes 2012) which, as we will argue, may be achieved through *internal* coordination within firms.

A critical perspective on geographic proximity and external coordinators

The exchange of quickly degrading waste and by-products, such as steam and heat, requires geographic proximity (Lombardi and Laybourn 2012; Shi et al. 2010). Moreover, low value materials, materials which are costly to transport and materials subject to strict (environmental) transport regulations benefit from geographic proximity (Lyons 2007). Nevertheless, plenty IS exchanges remain viable over long distances, for example mineral, ash, slag, metal and several chemical wastes. Moreover, avoided landfill taxes and other costs savings may render low-value materials viable for long-distance IS exchanges.

Literature already challenges the importance of geographic proximity and external coordination for IS exchanges (Walls and Paquin 2015). Supply chain literature shows that trust is not a prerequisite for business transactions (Dwyer et al., 1987; Vanpoucke et al., 2014), hence reducing the need for social proximity generated by geographic proximity and external coordinators. Furthermore, Lombardi and Laybourn (2012) discarded the element of geographic proximity from their redefined definition of IS by arguing that network participation enables IS and that network participation does not rely on geographic proximity since it also occurs in global supply chains. We argue that IS can develop without external coordinators and geographic proximity by pointing to global supply chain literature too. Supply chain literature provides ample examples of firms being able to create trust, exchange knowledge and engage in innovations by developing social ties with other firms in an international and complex environment without the support of external coordinators (so, under initially limited social and cognitive conditions) – see for example Meixell and Gargeya (2005) and Oke et al. (2013). One reason is that today's advanced information technologies and knowledge networks are often not spatially bounded. Moreover, as personal relationships create social and cognitive proximity, bringing people together through travel offers a possibility to circumvent the need for geographic proximity and external coordinators (Boschma 2005).

Nevertheless, to the best of our knowledge, all described IS cases show either or both geographic proximity and external coordinators, demonstrating the crucial role of both factors. In the following paragraphs we propose how *internal* coordination may fulfill the enabling role of geographic proximity and external coordination.

The role of internal coordination

Internal coordination may fulfill some similar aspects as geographic proximity and external coordinators. In long-distance IS exchanges, production managers from both ends of the IS exchange likely meet on a less frequent basis. Instead, purchasing managers (located at corporate headquarters) take over the tasks and responsibilities previously assigned to the production managers in IS (Chertow and Ehrenfeld 2012; Quintens et al. 2006). The purchasing manager's potentially limited experience, myopic (supply chain and financially related) perspective and lack of knowledge about manufacturing, may lead to selecting incapable IS suppliers or ineffective problem solving with suppliers (Swink and Schoenherr 2014). This is particularly likely in complex situations (Hung 2014), like IS exchanges (Küçüksayraç et al. 2015). Internal coordination between purchasing and manufacturing may mitigate such problems by enabling purchasers to obtain a solid understanding of the needs of manufacturing (Swink et al. 2007), as such increasing both manufacturing and purchasing performance (Narasimhan 2001; Swink et al. 2007). Practices leading to increased internal coordination include cross-functional teams, information sharing, training and joint decision making. So, internal coordination increases the cognitive proximity of the persons in charge of the IS exchange. Nevertheless, the role of internal coordination within our research context remains underexplored and internal coordination between purchasing and manufacturing might not fully substitute the benefits of social proximity created by geographic proximity and external coordinators (that is, creating strong social ties between IS partners) or cognitive proximity, hence requiring further research.

Figure 1 depicts our conceptual model. The absence of geographic proximity and external coordinators may have a negative impact on the firm's ability to set-up IS exchanges and to improve IS exchanges whereas internal coordination may have a positive impact. As IS aims to *economically* reduce *environmental* impacts (Chertow 2000), we define IS performance in terms of virgin material substitution rates, the recovered value of the waste material and induced transport as well as economic performance.

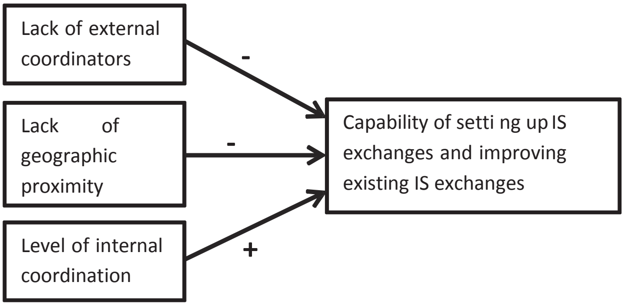

Figure 1 Conceptual model

Methods

The purpose of this research is to inductively build a perspective on firm-level challenges of IS exchanges. A case study approach is appropriate due to the lack of research on this topic and the exploratory nature and aim of this study (Eisenhardt 1989). A case study approach allows us to 1) obtain insights into 'how' and 'why' questions, 2) consult multiple observations on complex processes and 3) gain an holistic and in-depth initial understanding of the firm-level challenges (Eisenhardt 1989; Yin 2013).

Case selection and case introduction

We conducted an in-depth case study involving IS exchanges between one buyer and three different suppliers in the cement industry. The cement industry was chosen because of its pivotal role in circular economies (van Oss and Padovani 2003) and its long history of IS exchanges (van Oss and Padovani 2002), see for example the cases of Kalundborg, Denmark (Jacobsen 2006), Gladstone and Kwinana, Australia (van Beers et al. 2007) and Ulsan, South Korea (Behera et al. 2012). ''Cema'', the buyer studied here, is a European cement manufacturer. The first IS exchanges at Cema stem from the 70's, but remained local until 2009. Economic reasons as well as the limited availability of suitable waste at a local level eventually led to several cross-border IS exchanges, including the import of refuse derived fuel (RDF) – an otherwise landfilled waste of recycling firms. After sorting out precious materials such as metals and plastics, recycling firms have to dispose the non-recyclable residues. The energy content of the non-recyclable residues offers a possibility to reduce the fossil fuel usage of combustion processes, such as cement kilns.

The IS exchange under investigation, RDF, is chosen for four principal reasons. First, previous IS studies already consider energy recovery through waste combustion (for example Behera et al. (2012) and Mirata and Emtairah (2005)). Second, in the sourcing country under study, RDF is a relatively new practice, attributable to steep increases in landfill tax in recent years, as such rendering the RDF market relatively unexplored and the suppliers inexperienced with RDF exchanges. Therefore, the chosen market offers conditions which are representative to typical IS exchanges – waste exchanges between otherwise unrelated entities from different industries (Chertow 2000). Third, Cema sources RDF from multiple suppliers. Studying multiple IS exchanges allows us to compare different supply cases, contributing to obtaining a solid understanding of IS challenges (Eisenhardt 1989). Fourth, with RDF accounting for a substantial part of the fuel consumption, RDF has a profound impact on various production parameters such as capacity, clinker quality and emission limits, therefore requiring consensus between manufacturing and purchasing. Moreover, geographic distances between the involved persons (see table 2) increase the need for internal integration. As such, RDF at Cema offers fertile ground to investigate firm-level challenges and the role of internal coordination. Table 1 presents the main characteristics of each IS exchange.

Table 1 Supplier characteristics

Supplier	***Distance between Cema and the supplier (as the crow flies)***	***Weekly amount of waste based on 2015 figures***	***Length of the relationship***
A	815km	750 tons	Since 2012
B	860km	600 tons	Since 2015
C	830km	375 tons	Since 2012

Cema manages each IS exchange in a similar way. The purchasing department identifies IS suppliers and negotiates the contracts. Moreover, purchasing monitors the day-to-day performance of the suppliers and provides the suppliers with feedback. The production department, supported with analyses from an internal R&D lab and an independent lab, provides purchasing with supplier performance reports.

Data collection and data analysis

This research uses inductive methods to draw out the firm-level challenges of IS exchanges. Our research relies on both qualitative and quantitative data collection methods, providing us with rich insights (Jick 1979; Mintzberg 1979; Yin 2013).

The core of the data collection consisted of semi-structured interviews with informants from Cema as well as daily interaction with all people involved in the IS exchanges (including one supplier) during a four-month period – see Table 2. To get familiar with challenges of the IS exchanges under investigation, initial interviews and talks revolved around identifying issues related to the aim of our research. Based on these insights, subsequent interviews with key informants (see table 2) allowed us to probe emerging IS challenges and the role of internal integration (Eisenhardt 1989). We recorded and transcribed the interviews with the key informants verbatim for further analysis. As respondents may have the tendency to filter out events that do not fit or that render their story less coherent (Eisenhardt 1989), we verified individual statements by asking similar questions to multiple informants, checking statements with quantitative data and by checking statements during day-to-day conversations. Moreover, we triangulated the data with archival sources, including corporate presentations, supplier evaluation reports, supplier communication history and production data (Jick 1979). This additional and supplemental data increased the construct validity of our study (Voss et al. 2002; Yin 2013).

To cope with the rich amount of data, we first coded the interview statements which linked to the aim of our research. Multiple challenges arose and we initially analyzed each challenge separately. We composed case write-ups of each emerging IS issue based on the qualitative data from the interviews (Eisenhardt 1989) and we coupled the case write-ups with quantitative data (graphs and tables) to become intimately familiar with each challenge. We subsequently looked for similarities and differences between the challenges to gain an understanding of their underlying reasons – eventually abstracting four categories: '*ignorance of the other's business'*, '*legal issues'*, '*lack of incentives'* and '*lack of understanding between production and purchasing'*. For example, we coded 'it is difficult for them [sourcing] to understand the issues it [poor quality RDF] can give us [production]' as 'lack of understanding between production and purchasing' and we coded 'the suppliers have no interest in improving the quality [of the RDF] as long as they are able to get rid of it' as 'lack of incentives'. To facilitate reliability and validity, we used NVivo throughout the data analysis to manage the qualitative data analysis process (chain of evidence, data storage and overview of the coding) and we used SPSS and Excel for the quantitative data (Yin 2013). We present our findings below.

Table 2 Overview of the interviews

#	*Function*	*Relation to IS*	*Firm and location***	*Number of interviews*	*Total duration of the interviews*	*Interview date*
1	Facility manager	Overall overview RDF activities	Cema; Local office	1	2 hours	Nov, 2015
2	Category manager	Handling the RDF (tactical level)	Cema; Local office	2	5 hours	Nov, 2015
3	Production support	Handling the RDF (operational level)	Cema; Local office	2	2 hour	Nov, 2015
4	Supply chain manager	Performance of RDF suppliers (tactical level)	Cema; Local office	5	10 hours	Sep, 2015 – Jan 2016
5	Purchaser*	Performance of RDF suppliers (operational level)	Cema; Local office	7	5 hours	Sep, 2015 – Jan 2016
6	Strategic sourcing manager*	Sourcing new RDF suppliers and negotiating contracts	Cema; Head office	3	10 hours	Nov, 2015 – Jan, 2016
7	Researcher	Emissions of RDF	Cema; Lab	5	1 hour	Nov, 2015
8	Environ-mental engineer	Emissions of RDF	Cema; Local office	1	0.5 hour	Oct, 2015
9	Environ-mental manager	Emissions of RDF	Cema; Local office	1	2 hours	Oct, 2015
10	Lab engineer	Measuring RDF quality	Cema; Local office	1	1 hour	Nov, 2015
11	Production manager A*	Production control (tactical level)	Cema; Factory	2	4 hours	Dec, 2015
12	Production manager B*	Production control (tactical level)	Cema; Factory	8	20 hours	Oct, 2015 – Jan, 2016
13-17	Operators (5 persons)	Production control (operational level)	Cema; Factory	1	5 hours	Oct – Jan, 2015
18	Project leader production	Storage of RDF	Cema; Factory	2	3 hours	Nov – Dec, 2015
19	Operations manager*	Overall RDF performance of supplier A	Supplier A	1	1 hour	Dec, 2015

* Key informants.
** The local office is located on the factory but is physically detached from the factory offices. The lab is located next to the factory. The head office is located ca. 300km away from the factory.

Results

We present our results in line with our conceptual model (figure 1). We first present the role of internal integration in relation to both setting up the initial IS exchange and improving the performance of IS suppliers. We then present the remaining firm-level challenges.

The role of internal coordination

Our data suggest that internal integration helps to determine the impact of IS on production performance, hence allowing Cema to provide appropriate incentives to suppliers and to improve supplier selection. Moreover, internal integration assists supplier improvement initiatives at Cema.

First, Cema's suppliers lack sufficient incentives to improve their performance. As stated by Cema's purchaser: '*they don't do anything to improve their performance*' and '*the suppliers have no interest in improving the quality [of the RDF] as long as they are able to get rid of it' (production manager A)*. The operations manager of supplier B confirms this by stating: '*when you want the perfect waste, you have to pay us a lot of money. It is a costly process to remove undesired materials'*.

However, our data suggests that, without internal integration, purchasing lacks a complete understanding of the impact of RDF on production. As production manager A explains: *'[purchasing] thinks that as long as the gate fee and CV [energy content] is okay, then the lack of quality is not really a problem'*. Although this claim is not entirely true – purchasing focuses on many other quality aspects such as moisture and heavy metals – purchasing does not take into account the somewhat more hidden costs. For example, analyzing the RDF usage reveals significant production losses related to variations in calorific value, moisture and blockages caused by pieces of metal scrap in the RDF. Furthermore, production data shows that quality issues with RDF impacts CO, CO2 and dust emissions, not only having an environmental impact, but also resulting in an increase in environmental taxes payable. The purchasing department, however, is unaware of the full impacts and does not use the accompanied costs to provide incentives to IS suppliers or to select new IS suppliers. Production manager A explains this as follows: *'it is difficult for them [the purchasing department] to understand the issues that it [the poor quality RDF] can give us… If we could somehow systematically visualize the extra costs, it would be easier to make better decisions'*. So, our data suggests that increased internal coordination through information sharing and the involvement of production employees in working with IS suppliers – for example cross-functional teams and joint decision making – contributes to providing additional incentives to suppliers for improving their performance. In addition, the richer insights into the (hidden) costs of RDF contribute to supplier selection decisions by providing appropriate selection criteria.

Second, internal coordination contributes to supplier improvement initiatives by increasing the understanding of each other's business. For instance, supplier B delivered RDF which contained large pieces of scrap metal, clogging the outlet of the pre-calciner and hence causing production stops. Supplier B only understood the problem after a plant visit where they talked with Cema's production employees and a technical team, eventually allowing them to understand and improve on the issue. Likewise, solving an issue with supplier A took a long time because both Cema and the supplier did not understand the origin of the problem. The supplier was unaware that textiles treated with fire retardant caused problems at Cema because of Cema's distinct production set-up and Cema was unaware of the fire retardant in the RDF. Cema understanding the supplier's business helped solving the problem in due time. As production manager A explained: *'so what was really key here was the vendor's information, telling us that he had actually put in a lot of this material [textiles treated with a flame retardant]… it helped us [production] understanding what the problem was'*. So, internal coordination such as joint problem solving in which knowledgeable persons – in this case production employees and a technical team – support purchasing managers, helps to improve supplier performance.

Nevertheless, despite the positive role of internal integration, several firm-level issues remained unsolved. The next section will elaborate on the remaining firm-level challenges.

Firm-level challenges in the context of long-distance IS exchanges without external coordinators

Our data suggests that the absence of geographic proximity and external coordinators hinders the selection of appropriate RDF suppliers, despite Cema's capability to identify appropriate markets and, as we illustrated in the previous section, to draft appropriate selection criteria. As Cema's sourcing manager explains, '*we didn't know the market outside [the home country] when we started looking abroad… so when going to other markets we started without any knowledge*'. Information such as how much and what types of waste a market generates and how suppliers process the waste (which might be subject to legislation) determines the suitability of the market. For example, '*[The specific type of high quality RDF] we have [in the local market] is because these suppliers are the only suppliers in the world who deliver this waste … the waste comes from a special process that is only done by local suppliers because of the legal framework here'* (sourcing manager). Nevertheless, Cema was able to collect the required information and to identify suitable RDF markets by means of a market study: '*it [finding the market] is not difficult, the only issue is to find the best supplier*' (sourcing manager). However, the lack of transparency about the waste quality and the capabilities of individual suppliers often formed an obstacle for assessing RDF quality: '*you don't know what problems you are facing … You cannot specify everything, we need to have the experience with the material'* (sourcing manager). Cema, therefore, performs test deliveries before making an agreement but potentially unstable processes of the suppliers as well as the limited insights deriving from a limited number of test samples resulted in the selection of low-performing IS suppliers. In fact, every single delivery of the suppliers under investigation deviated from the minimum standards agreed upon whereas the suppliers in the home market were able to live up to their, often even higher, standards.

Furthermore, legislation may prohibit or complicate certain long-distance waste exchanges: '*meat and bone meal [a type of RDF] cannot be transported over long distances due to legal demands*' (sourcing manager). In addition, adding global IS suppliers may require a new supply chain design in order to adhere to long-distance waste transport legislation: *'it was totally different ... We needed to develop a new method for receiving waste by ship … The whole supply chain had to be developed'* (sourcing manager). The changes involved packaging the RDF, handling the RDF at both the supplier's site and Cema's site and safety restrictions during transport. As a result, implementing the new supply chain was challenging: *'it was not easy, because we [both the supplier and Cema] did not have the experience … we had a lot of problems'* (sourcing manager). Nevertheless, as both Cema and the suppliers became more experienced with long-distance RDF transportation, the initial issues were resolved: *'it takes, in our experience, some years because you need to know all the traps you can fall into*' (production manager A). Moreover, the gathered experience eased the adherence to legal requirements when contracting supplier B, two years later. In addition, Cema anticipates upon upcoming political changes when selecting suppliers as political changes may have an impact on the availability of RDF as legislation may change how waste is generated and processed.

In sum, we found a positive role for internal integration in long-distance IS exchanges without the support of external coordinators. Nevertheless, some firm-level challenges remained. Figure 2 summarizes our findings in relation to our conceptual model.

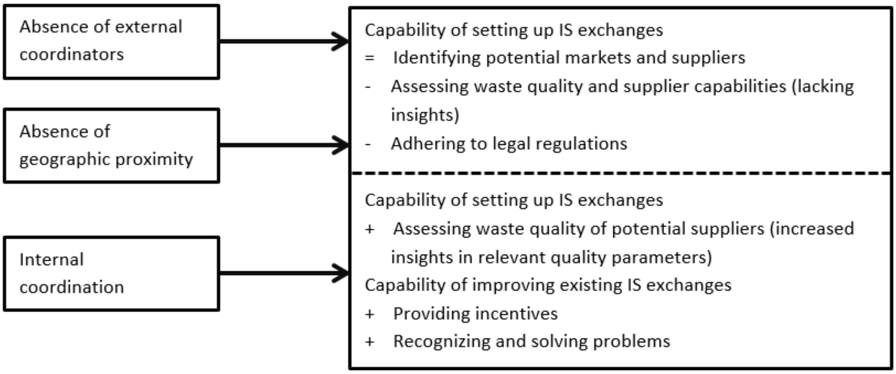

Figure 2 Summary of the results (- means reduced capability, = means largely unaffected capability, + means increased capability)

Discussion

Given the exploratory nature of this study, in the previous chapter we presented the role of internal coordination as well as the firm-level challenges without geographic proximity and external coordinators. In the following sections we discuss our results in more detail.

The role of internal coordination

In the literature review we argued that external coordinators and geographic proximity supports buyers in selecting IS suppliers (Sterr and Ott 2004; Mirata and Emtairah 2005) and helps to identify ways to increase IS performance (Robertson and Langlois 1995). Our results suggest that internal coordination plays a similar role as it helps suppliers to translate the identified costs into financial incentives to stimulate appropriate supplier behavior such as improved performance on waste quality. Furthermore, internal coordination helps to improve the buyer's supplier selection capabilities by providing insights into which supplier characteristics are important. Finally, internal integration increases the efficiency of supplier improvement initiatives in IS exchanges by identifying (urgent) issues and solutions by increasing the understanding of each other's business, hence helping to diagnose the root cause of the issue and to act accordingly. As suggested by Boschma (2005), the above benefits derive from the increased cognitive ability of the persons involved, through their increased knowledge base and a better understanding of each other's business. Our findings suggest that, in IS, internal integration may increase the cognitive proximity through:

1. Educating and supporting purchasing managers about the cost structure of IS.
2. Increasing the understanding of the supplier's processes and its effect on the waste quality.
3. Increasing the quality of supplier communication, hence increasing the supplier's understanding of the buyer's needs.

Our insights are in line with supply chain management literature (Zhao et al. 2011) and complement the findings of Robertson and Langlois (1995), who found that the awareness of problems and solutions supports IS development.

Furthermore, our findings build upon previous work by Park and Park (2014) by stressing the importance of financially assessing the business case by including the additional costs of low-grade waste (for instance lost production and quality issues). Our study suggests that internal coordination helps to understand (the otherwise hidden) cost structure – a finding well-established in supply chain literature (see for example Kuei et al. (2001)). Our research, as a case in point, shows that IS may result in significant hidden costs due to the ambiguous effects on production performance, as such exemplifying the importance of internal integration.

Nevertheless, despite the positive role of internal integration, our data reveals remaining firm-level challenges, which we discuss in more detail in the next section.

Firm-level challenges in the absence of both geographic proximity and external coordinators

First, our research builds upon the findings of Mirata (2004) and Sterr and Ott (2004) by providing insights into the challenges deriving from a lack of transparency due to the absence of adjacent suppliers and external coordinators. Our research suggests that a lack of transparency does not limit firms in identifying potential markets for long-distance IS exchanges, but complicates the assessment of the suitability of individual suppliers. Whereas geographic proximity increases the transparency of supplier capabilities through easing the acquisition of (tacit) knowledge due to social proximity (Boschma 2005) and whereas external coordinators may connect suitable IS partners (Boons and Spekkink 2012; Paquin and Howard-Grenville 2012), internal coordination falls short on obtaining (tacit) knowledge and transparency about supplier capabilities during the supplier selection process. As such, our results suggest that while internal coordination may replace the cognitive proximity component of geographic proximity and external coordinators, it may not fully replace the benefits related to social proximity. The resulting lack of transparency reduces IS performance (Sterr and Ott 2004; Swink and Schoenherr 2014). Moreover, our findings build on the findings of Jensen et al. (2011) as we found that transparency of supplier capabilities is needed in IS to assess the soundness of the business opportunity; social proximity and therefore geographic proximity and external coordinators (as suggested by Jensen et al. (2011)) may play an important role in this.

Second, our results suggest the existence of firm-level challenges related to legal restrictions and requirements for long-distance IS exchanges. At Cema, the transportation of cross-border IS exchanges is subject to legal requirements affecting the allowed waste types for long-distance transport and the waste handling processes on both the buyer’s and the supplier’s site. Moreover, in line with Hammond and Beullens (2007) we found that deviating legal requirements between geographical areas such as regions and countries may affect the type and quality of the available waste – a factor firms should take into account when engaging in long-distance IS exchanges. Furthermore, our results indicate an additional legal firm-level challenge as cross-border IS exchanges may be affected by changing legislation – both in terms of legal requirements and market development (affecting the availability of suitable waste). Nevertheless, our results indicate that firms benefit from the gathered experience in previous IS exchanges: firms can use the gathered experience when adding new suppliers who are located within the same geographic market through applying previously acquired knowledge. So, our findings suggests that external coordinators can contribute by assisting firms with initial IS exchanges in geographic areas subject to legal requirements currently foreign to them. Moreover, external coordinators may help firms to anticipate on political changes and to select suitable markets. Our findings, as such, contribute to further defining the role of external coordinators (Paquin and Howard-Grenville 2012).

Finally, it should be noted that our insights as well as a firm’s decision to increase internal coordination should be considered along with the identified transaction costs of IS, namely search costs, negotiation costs and contract enforcement costs (Chertow & Ehrenfeld 2012) and the cost of internal integration.

Conclusion

Our exploration of the challenges of long-distance IS exchanges without the support of external coordinators offers insights into firm-level challenges and the role of internal coordination. In case of dissatisfying performance of IS suppliers, our research suggests that internal coordination may reveal additional options and directions for buyers to provide appropriate incentives to suppliers. Moreover, our research highlights the potential role of internal integration to make both the buyer and the supplier in the IS exchange aware of problems and solutions, enabling them to act accordingly. As such, internal integration may act as a substitute for geographic proximity and external coordinators.

Nevertheless, our case study suggests that internal integration does not fully substitute geographic proximity and external coordination. Our research suggests that a lack of transparency of the suppliers' business as a result of the absence of geographic proximity and external coordinators impairs the assessment of IS supplier capabilities. Moreover, we also found that long-distance IS exchanges might suffer from a myriad of legal obstacles when external coordinators are not available to offer legal support.

To conclude, the novelty of this research lies in 'uncovering' a case in the absence of geographic proximity and external coordinators – two key enablers for IS. In doing so, we explored firm-level challenges and the role of internal coordination and we showed that long-distance IS exchanges without external coordinators can be feasible. In sum, this research provides both firms and literature with initial insights and contributes toward achieving the enchanting prospects of closing global material loops.

This research is not without limitations. The relationships studied here are dyadic and involve only one type of waste. So, a limitation of this study is the inability to incorporate a wider variety of waste exchanges derived from a wider set of industries and issues such as waste quality might be largely an issue for RDF and might be less prevalent in other waste exchanges. However, as shown in the methods section, RDF as used by Cema resembles typical IS exchanges. Therefore, we do not expect serious bias toward our findings. Moreover, as we only focused on waste exchanges from one country, a limitation of our study is that possible cultural impacts on the social aspect of IS (that is cooperation, commitment of parties, trust, etc.) are not included. Furthermore, as our findings are based upon a single case, factors such as firm size, power between the buyer and the supplier and the significance of the exchanged waste for both the buyer and the supplier are not taken into account. Such factors may affect the buyer's capability of selecting suppliers and working with them. Finally, the single-case study design limits our understanding of the impact of internal integration as proximity between internal departments affects the appropriate level of internal integration (see table 2). We suggest for future research that confirmatory work investigates different waste exchanges in different countries in different organizational contexts to increase the generalizability and validity of our findings. Nevertheless, we believe we have made a first important step by exploring the firm-level challenges of long-distance IS in the absence of external coordinators.

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PAPER II

Prosman, E.J. and Wæhrens, B.V. (2018), "Tracing the origin in commodity supply networks: an input-output approach based on trade data", submitted for a first round of review at the *International Journal of Production Economics*. An earlier version of the paper is presented at the 5th EurOMA sustainability forum in Kassel.

Tracing the origin in commodity supply chain configurations: an input-output approach based on trade data

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Abstract
Global supply chain configurations trade products from all over the globe. Such supply chain configurations often result in low transparency in terms of where (intermediate) products are produced, which can give rise to economic, environmental and social risks in a firm's supply chain configuration. To gain insights into economic risks such as the impact of natural disasters or trade wars or to gain insights into sustainability risk such as child labor and poor environmental practices, this paper presents a model to trace the origin of (intermediate) products. The presented model uses an input-output approach based on trade data. The model is exemplified on three different cases to illustrate the application of the model. Firms can use the insights from the model for decisions on where to source from, or to expend resources to make their supply chain configuration more resilient for economic disruptions, or to avoid sustainable issues in their supply chain. In addition, we show and discuss how the input-output model can be used for other purposes, such as byproduct souring. Besides the practical contribution, this paper contributes to literature on supply chain traceability.

Keywords: byproducts, transparency, sourcing, commodity trading, supplier chain configurations

1. Introduction

In today's world, supply chain configurations often stretch the entire globe and many commodities, such as agricultural products, raw materials and chemicals, are traded and shipped between many countries (Gunasekaran et al., 2015). In these global supply chain configurations, firms have to consider numerous economic risks due to unforeseen disruptions in the supply chain (Blackhurst et al., 2011; Christopher and Peck, 2004; Pettit et al., 2013) while also accounting for environmental and social risks (Goh et al., 2007). Indeed, a single disruption or a single environmental or social scandal may negatively affect the entire supply chain (Chopra and Sodhi, 2014). Hence, firms must identify and act upon supply chain risks to thrive in today's global world.

A great deal of literature addresses how firms can take countermeasures to respond to disruptions in their supply chain. For example, firms can increase supply chain resilience by increasing inventory levels, dual sourcing, demand pooling, postponement and in-house production (Chopra and Sodhi, 2004; Ali et al., 2017; Hendricks and Singhal, 2003; Tang, 2006). Furthermore, collaborative planning and the exploitation of upcoming technologies such as blockchain and the internet of things can provide transparency to detect supply disruptions at an early stage (Cole, 2018). Furthermore, with regards to mitigating environmental and social risks, third-party certificates or sustainability assessments can facilitate transparency to detect and avoid issues at an early stage (Stiller and Gold, 2014; Müller et al., 2009).

Unfortunately, those countermeasures have their downsides. For example, raising inventory levels results in increased costs and might hide problems in the supply chain (Stevenson, 2009); adding suppliers increases the complexity of managing the supply chain configuration (Chopra and Sodhi, 2004); investing in blockchain technology and internet of things devices can turn out costly; and sustainability assessments come at a cost as well (Wieland and Handfield, 2010). Moreover, transparency (e.g. through blockchain technology and collaborative planning) is often hard to achieve beyond the first tiers in a multiple-tier supply chain configuration. New connections which emerge over time in the supply chain configuration can further complicate the realization of transparency (Bode and Wagner, 2015). Therefore, firms benefit from insights, which help to allocate their finite resources to the areas in the supply chain configuration which are most vulnerable to economic disruptions or environmental and social issues (Batt and Purchase, 2004).

To mitigate disruptions and avoid social and environmental risks in the supply chain configuration without eroding profits, firms need insights into the risks imposed by the supply chain configuration. Tracing the *country of origin* of the traded products in the supply chain configuration provides a first starting point for a risk assessment of the supply chain configuration. The following examples show how many of the culprits for economic, environmental and social risks in supply chain configurations derive from the country of origin: i.e. where the (intermediate) products are produced, mined or grown. For example, the 2011 Tohoku earthquake damaged petrochemical complexes (including production facilities of hydrogen peroxide, a chemical compound used to produce semi-conductors), high-tech component manufactures and infrastructural links (Matsuo, 2015). The damage resulted in severe supply disruptions for products containing display components, electronic components, semi-conductors, batteries and hard disks (Matsuo, 2015). Natural disasters can also affect crop yields and disrupt food supply chains. Moreover, disasters at large production complexes, perhaps most famously the lightning bold causing a shut-down at the Philips Semiconductor plant in Albuquerque New Mexico in March 2000, can cause major supply disruptions (Tomlin, 2006). Besides natural disasters, trade embargos and trade wars are other potential sources of economic supply chain disruptions displayed at a country level. Likewise, many environmental and social scandals have their roots in the country of origin of complex supply chain configurations. Take for instance the toxic waste from the manufacture of Apple products or sweatshop and penurious labor conditions at NIKE's, Gap's and Levi-Strauss' overseas (sub) suppliers (Zadek, 2004; de Brito et al., 2008; Tachizawa and Wong, 2015). Although these companies initially declined social responsibility, they eventually had to shift stance due to public pressure (Zadek, 2004; de Brito et al., 2008). The above examples illustrate that tracing the *country of origin* of the (intermediate) products in the supply chain configuration provides useful clues for mitigating economic, social and environmental risks in the supply chain. However, tracing the country of origin is often a complicated task and, to the best of our knowledge, literature does not address how firms can trace the countries of origin in a supply chain configuration.

To address this gap in literature, this paper presents a model to trace the country of origin of products in a global supply chain. The presented model is based on trade data and relies on the input-output approach introduced by Leontief (1951). Input-output modelling is often used for policy making (La Noce et al., 1993), for consequential life cycle assessments (Yang, 2016) and has found its way into supply chain management too (Albino et al., 2002; Albino and Kühtz, 2004; Aviso et al., 2011) The model presented in this paper contributes to research by creating insights into the countries of origin in supply chain configurations, thereby extending supply chain traceability beyond first- and second-tier suppliers. In doing so, this research contributes to the quest for new methods to achieve resilient supply chains (Christopher and Holweg, 2011). Moreover, to date, the social aspect of sustainability is often neglected in research and practice (Wu and Pagell, 2011; Pagell and Wu, 2009). The model presented in this research offers a novel tool to avoid social (and environmental) scandals in global supply chain configurations. In addition, the model can be exploited for sourcing byproducts in the context of industrial symbiosis (see literature review).

The article is organized as follows. First, we present the current literature on managing economic, environmental and social risks in supply chain configurations. We then present the model and exemplify the use of the model on both fictional and real-life supply chain configurations. In addition, we illustrate an alternative use of the model, by utilizing the model for sourcing byproducts in a real-life case of industrial symbiosis in the circular economy. We conclude with a discussion of the model where we also discuss the assumptions and the weaknesses.

2. Literature review

Firms increasingly rely on their supply chain configuration due to the increased focus on core competences and the outsourcing of less profitable activities (Gunasekaran et al., 2015). As described in the introduction, the reliance on supply chain configurations imposes economic, environmental and social risks on firms. The next paragraphs describe each of these risks in more detail and elaborate on how tracing the country of origin provides useful insights for risk mitigating efforts. In addition, the benefits of tracing the country of origin for sourcing byproducts as part of industrial symbiosis and circular economy practices are presented too.

2.1. Economic risks: disruptions in the supply chain

Disruptions in the supply chain are inevitable occurrences in today's global and turbulent world (Skipper and Hanna, 2009). Therefore, a proactive approach towards preparing for disruptions in the supply chain attracts an increasing amount of interest from both academics and practitioners (Scholten and Schilder, 2015; Ali et al., 2017; Sheffi, 2015). The literature review of Ali et al. (2017) highlights the importance of visibility in the supply chain and situation awareness as key elements to prepare for supply disruptions.

Supply chain visibility and situation awareness refer to the ability to discern disruptive events (Priya Datta et al., 2007) and map the vulnerabilities in supply chain configurations (Fiksel et al., 2015). Insights deriving from high supply chain visibility and high situation awareness help firms to allocate resources to mitigate the risks of potential disruptions in their supply chain configuration. For example, high supply chain visibility and high situation awareness may lead to changing the supply chain configuration, adding redundant capacity to the supply chain or increasing stock levels at different points in the supply chain configuration (Ambulkar et al., 2015). However, building supply chain visibility and situation awareness often requires coordination and information sharing between supply chain partners as well as investments in IT solutions, which provide transparency in the supply chain (Melnyk et al., 2010; Jüttner and Maklan, 2011; Brandon-Jones et al., 2014; Vargo and Seville, 2011).

Unfortunately, achieving sufficient supply chain visibility and situation awareness can be an expensive endeavor. Moreover, implementing IT solutions and engaging in collaboration beyond the first tiers in the supply chain may be difficult (Bode and Wagner, 2015).

Yet, the consequences of not knowing the point of origin of products can be fatal, especially when the time for recovery is long. Failing to incorporate the entire supply chain may lead to a supply chain which is not as resilient to disruptions as it seems to be – see figure 1 for an example. In both cases in figure 1, the focal firm might think the implemented dual sourcing strategy prepared them for disruptions at the country of origin. However, only in the second case, one can speak of ‘true’ dual sourcing.

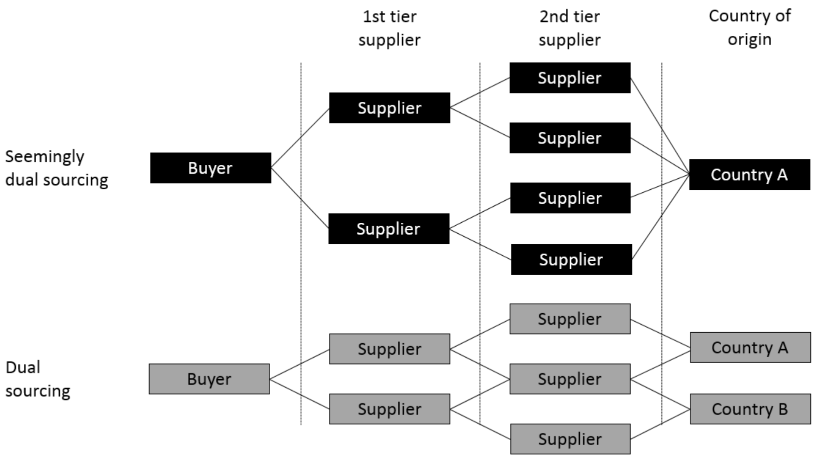

Figure. 1. *The effect of supply chain visibility on the effectiveness of dual sourcing aimed at mitigating supply disruptions in the country of origin*

Furthermore, tracing the country of origin in the supply chain configuration can help firms to avoid redundant investments in resilience strategies. When the countries of origin do not impose a significant risk – e.g. when the countries of origin are in different geographical locations and have a stable political and economic climate – investments can be saved. Instead, resources might be better spent elsewhere (Batt and Purchase, 2004), for example in parts of the supply chain which imposes a significant risk. Hence, firms can benefit from a method to trace the origin.

2.2. Environmental and social risks

Ample research has been undertaken to address environmental and social sustainability in supply chain configurations, of which reviews haven been written by, amongst others, Govindan et al. (2013) and Gimenez and Tachizawa (2012). However, literature seems to be limited to sustainability within the proximate supply network, i.e. often not extending first- or second-tier suppliers. In fact, literature argues that managing sustainability in the supply chains is often a task of the purchasing function, i.e. selecting suppliers based on sustainable supplier selection criteria (Wilhelm et al., 2016).

Sustainable supplier selection criteria may incorporate a wide range of sustainable factors. Examples include product design for reuse, green packaging, reverse logistics, environmental management systems such as ISO-14001, up-to-date environmental permits, the use and emission of harmful substances, staff training on environmental issues, health and safety practices, employment compensation and employee diversity (Bai and Sarkis, 2010; Freeman and Chen, 2015; Govindan et al., 2013; Handfield et al., 2002; Lu et al., 2007; Zhu and Sarkis, 2004). To aid firms in selecting suppliers, literature offers models which buyers can use to select suppliers based on multiple sustainability criteria. For example, Freeman and Chen (2015) consider multiple sustainability objectives in their AHP-Entropy-TOPSIS framework for supplier selection. Furthermore, Hsu and Hu (2009) propose an ANP model for supplier selection which considers sustainable capabilities in the supplier's procurement and R&D departments and the supplier's processes. Other models include the Chi-Squared Test (Vachon and Klassen, 2006), Data Envelopment Analysis (Kumar and Jain, 2010) and the fuzzy inference method (Humphreys et al., 2006). However, all those models focus on the sustainable performance of the first-tier supplier.

In fact, Wilhelm et al. (2016) highlights the crucial role of the first-tier supplier as an agent for disseminating sustainability standards in the multi-tier supply chain configuration via their first-tier supplier. However, whether upstream suppliers accept this responsibility and start to introduce sustainability in their upstream supply chain activities might be questionable. Power imbalances between buyers and suppliers, for instance, may lead to supplier's who are unwilling to embrace the desired sustainable standards (Prosman et al., 2016). Furthermore, assuring the dissemination of sustainability standards often becomes an ambiguous undertaking since suppliers might be globally dispersed, situated in remote locations or may not have access to collaborative technologies. Finally, suppliers may deliver products to other supply chains – which might have different (sustainable) objectives. This might result in a conflict on interests about which sustainable standards to follow as suppliers might have to adhere to a wide array of sustainability standards, which differ in importance (Raj Sinha et al., 2004).

Therefore, relying on the first-tier supplier and assuming further dissemination of sustainability standards in the lower tiers of the upstream supply chain may impose significant sustainable risks in the supply chain and may lead to environmental and social scandals. For example, Brazilian authorities argued that Zara's raison d'être is making clothes and that, therefore, Zara must know where its clothes are produced (Burgen and Phillips, 2011). By tracing the country of origin of the products traded in global supply chain configurations, firms can identify which parts of the supply chain rely on countries with low environmental and social standards (Färe et al., 2004). Such insights enable firms to focus on sustainable efforts on supply chain configurations with a higher sustainable risk (Maloni and Brown, 2006). In addition, guaranteeing environmental and social sustainability can lead to a sustained competitive advantage in an era of sharp international competition (de Brito et al., 2008).

2.3. Enabling industrial symbiosis: sourcing of byproducts

Another situation which benefits from insights into the country of origin of products is the utilization of waste and byproducts (Prosman et al., 2017). The practice of using waste and byproducts across industries, also known as industrial symbiosis (Chertow, 2000), forms a prime pillar on today's environmental and political agenda – see for example the Circular Economy Production Law of the People's Republic of China (The Standing Committee of the National People's Congress China, 2008) and the European Circular Economy package (European Commission, 2015).

Byproduct synergies often involve the exchange of byproducts such as ashes, slags and chemicals, see for example the case descriptions of Kwinana and Gladstone in Australia (van Beers et al., 2007), the national industrial symbiosis program in the United Kingdom (Jensen et al., 2011) or Kalundborg in Denmark (Jacobsen, 2006). The geographical origin of the product from which these byproducts derive may determine the quality of waste and byproducts. For example, fly ash from the combustion of Russian coal has very different properties than fly ash from the combustion of South African coal and might therefore be less useful for certain cement types. Furthermore, the quality of refuse-derived fuel (the residue waste fraction after recycling) differs between different countries based on the input for recycling and the maturity of the recycling system (Prosman and Sacchi, 2017). Hence, tracing the country of origin of the products from which waste and byproducts derive, can provide useful clues about waste and byproduct quality in different geographical markets and enables firms to better utilize byproducts from other industries by matching waste and byproduct quality with exacting production requirements (Prosman et al., 2017).

Unfortunately, waste and byproduct markets are often non-transparent due to the typical cross-industry nature of byproduct exchanges. Firms may therefore struggle to find suitable byproducts (Paquin and Howard-Grenville, 2009). As such, there as a need for methods which help firms to determine the country of origin of the products from which the byproducts derive.

In addition, tracing the origin of products within the supply chain configuration may have various other benefits for firms. For example, knowing the origin might lead to insights on how to minimize transport beyond the first-tier supplier. Furthermore, tracing the origin can help to determine product quality and quantity. For example, knowing the point of origin (and the local harvest conditions) reduces the complexity of preparing for supply risks which derive from quality and quantity of traded commodities which are affected by weather conditions (e.g. agricultural commodities) (Dittfeld et al., 2018). In conclusion, there is a need to support supply chain decisions systematically and at a wider supply chain level. For this purpose, we propose the input-output model explained in the next section.

3. Input-output model development

Input-output models show interdependencies in economies and are typically used to analyze the economic structure of regions in terms of material flows between different industries (Leontief, 1951). As illustrated in the following example, input-output models based on the trade between different economies can help to trace the country of origin of products in supply chain configurations.

Consider a simple supply chain configuration for product Y with only three countries in the entire supply network: Sweden, Norway and Denmark. The countries produce and trade product Y with one another – see Figure 2.

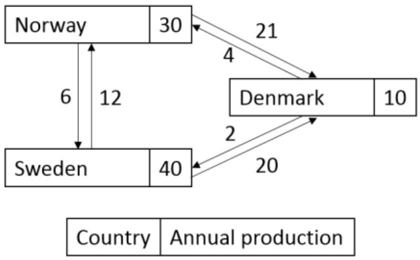

Figure. 2. *Supply chain configuration for product Y*

Norway produces 30 units of product Y, imports 12 units from Sweden and imports 4 units from Denmark. Hence, the total number of units of product Y in the Norwegian economy equals 46 (30 + 12 + 4). Out of these 46 units, 21 units are exported to Denmark and 6 units are exported to Sweden. So, 45.7% (21 / 46) of both the Norwegian production and the Norwegian import leaves the Swedish economy to Denmark. As Norway produces 30 units, 45.7% * 30 units ≈ 13.69 units of product Y produced in Norway are exported to Denmark. The remaining units of product Y which Norway exports to Denmark come from import: i.e. import from Denmark and Sweden. The above can be captured as:

$$Norwegian\ products\ leaving\ Norway\ to\ Denmark = \frac{Norwegian\ export\ to\ Denmark}{Sum\ of\ Norwegian\ import + Norwegian\ production} * Norwegian\ production$$

Or:

$$\frac{21}{16+30} * 30 \approx 13.69$$

When performing the same calculation for all trade operations in the supply network, we can enter the numbers in an input-output table – see Table 1.

Table 1. *Input-output table of trade and production of the entire supply network*

	Norway	*Sweden*	*Denmark*	*Production*
Norway	-	3.91	13.69	30
Sweden	10.43	-	17.39	40
Denmark	0.78	0.39	-	10

In the described equilibrium, for each unit produced in Denmark, Norway produces 13.69 / 10 ≈ 1.37 units to export to Denmark. Likewise, for each unit produced in Norway, Denmark produces 0.78 / 30 ≈ 0.03 units to export to Norway. When computing for all trade operations, the somewhat circular relationships can be described as:

$$Y_{Norwegian\ products\ in\ Norway} = X_{Norwegian\ production} - 0.10X_{Swedish\ production} - 1.37X_{Danish\ production}$$
$$Y_{Swedish\ products\ in\ Sweden} = -0.35X_{Norwegian\ production} + X_{Swedish\ production} - 1.74X_{Danish\ production}$$
$$Y_{Danish\ products\ in\ Danish} = -0.03X_{Norwegian\ production} - 0.01X_{Swedish\ production} + X_{Danish\ production}$$

$X_{Norwegian\ production}$, $X_{Swedish\ production}$ and $X_{Danish\ production}$ represent the total production in Norway, Sweden and Denmark respectively; $Y_{Norwegian\ products\ in\ Norway}$, $Y_{Swedish\ products\ in\ Sweden}$ and $Y_{Danish\ products\ in\ Denmark}$ represent their own products in their own economies. These three linear equations with three unknowns can be solved for any given $Y_{Norwegian\ products\ in\ Norway}$, $Y_{Swedish\ products\ in\ Sweden}$ and $Y_{Danish\ products\ in\ Denmark}$ where the outcomes show the entire production in the supply network. To do this, we enter the three linear equations into the following three matrices:

$$\begin{bmatrix} 1 & -0.10 & -1.37 \\ -0.35 & 1 & -1.74 \\ -0.03 & -0.01 & 1 \end{bmatrix} x \begin{bmatrix} X_{Norwegian\ production} \\ X_{Swedish\ production} \\ X_{Danish\ production} \end{bmatrix} = \begin{bmatrix} Y_{Norwegian\ products\ in\ Norway} \\ Y_{Swedish\ products\ in\ Sweden} \\ Y_{Danish\ products\ in\ Denmark} \end{bmatrix}$$

Here, AX = B.

From the production of each country, the X matrix, we can derive the contribution of each country to the number of products in the supply network. As $X = A^{-1}B$, we first take the inverse of A:

$$\begin{bmatrix} 1.08 & 0.11 & 1.66 \\ 0.42 & 1.04 & 2.39 \\ 0.03 & 0.01 & 1.04 \end{bmatrix}$$

From here, the general solution is:

$$\begin{bmatrix} X_{Norwegian\ production} \\ X_{Swedish\ production} \\ X_{Danish\ production} \end{bmatrix} = \begin{bmatrix} 1.08 & 0.11 & 1.66 \\ 0.42 & 1.04 & 2.39 \\ 0.03 & 0.01 & 1.04 \end{bmatrix} x \begin{bmatrix} Y_{Norwegian\ products\ in\ Norway} \\ Y_{Swedish\ products\ in\ Sweden} \\ Y_{Danish\ products\ in\ Denmark} \end{bmatrix}$$

Or:

$$X_{Norwegian\ production} = 1.08Y_{Norwegian\ products\ in\ Norway} + 0.11Y_{Swedish\ products\ in\ Sweden} + 1.66Y_{Danish\ products\ in\ Denmark}$$
$$X_{Swedish\ production} = 0.42Y_{Norwegian\ products\ in\ Norway} + 1.04Y_{Swedish\ products\ in\ Sweden} + 2.39Y_{Danish\ products\ in\ Denmark}$$
$$X_{Danish\ production} = 0.03Y_{Norwegian\ products\ in\ Norway} + 0.01Y_{Swedish\ products\ in\ Sweden} + 1.04Y_{Danish\ products\ in\ Denmark}$$

By plugging in a value for either $Y_{Norwegian\ products\ in\ Norway}$, $Y_{Swedish\ products\ in\ Sweden}$ or $Y_{Danish\ products\ in\ Denmark}$ one can now compute the related values for $X_{Norwegian\ production}$ $X_{Swedish\ production}$ and $X_{Danish\ production}$. For example, when Norway has 10 Norwegian products in their economy (so, $Y_{Norwegian\ products\ in\ Norway} = 10$) the results show that in the current equilibrium 10.8, 4.2 and 0.3 products are produced by Norway, Sweden and Denmark respectively. We can conclude that 70.5% of the products in the Norwegian market are from Norwegian origin, 27.7% of the products on the Norwegian market have their origin in Sweden and the remaining 1.8% of the products are produced in Denmark.

4. Model illustration

The examples presented in this section cover the three discussed applications in the literature review:

- Economic risks: supply chain disruptions in the ammonia supply chain
- Social and environmental risks: child labor in the cotton supply chain
- Enabling industrial symbiosis: sourcing of fly ash

The purpose of the examples is not only to illustrate the different uses of the model, but also to illustrate the model in different supply chain configurations such as more locally or more globally oriented supply chain configurations or many and few trade operations.

The trade data used in the examples is freely available at The United Nation's Commodity Trade Statistics (2015). The United Nation's Commodity Trade Statistics are compiled annually and contain matrix-style information on thousands of specific types of products classified by country of import and export. Although some countries invariably fail to provide all data (so import and export do not match), the import data is considered most reliable. The data used for this article is from the year 2015 (the most recent year for which data is available for all countries at the moment of writing).

4.1. Economic risks: supply chain disruptions in the ammonia supply chain

To illustrate the use of the input-output trade model to assess the risk of supply chain disruptions, the example refers to an actual supply chain configuration of ammonia. The ammonia is used to reduce the emissions of nitrogen oxides (NO_x) in cement making. An abrupt stop of ammonia supply will cause a production shutdown until new ammonia supply is secured as a lack of ammonia leads to unallowable NO_x emissions. According to the United States Geological Survey (USGS), outside cement making, ammonia is mainly used for fertilizers (USGS, 2016a). The cement manufacturer in the example sources the ammonia locally for their plants in China, Egypt, Malaysia, Turkey, Denmark and Belgium.

Ammonia is produced in 63 different countries (USGS, 2016a). China produces by far the largest quantity of ammonia while also Russia, India and the United States account for a large share of ammonia world production (USGS, 2016a). Table 2 provides a list of the largest ammonia producing countries in the world.

Table 2. *Excerpt of ammonia producing countries worldwide in 2015 (source: USGS, 2016a)*

Country	*Production (1000 metric tons)*	*Percentage*	*Cumulative Percentage*
CHN	49.706	34.3%	34.3%
RUS	12.000	8.3%	42.6%
IND	10.800	7.5%	50.1%
USA	9.590	6.6%	56.7%
IDN	5.000	3.5%	60.1%
TTO	4.905	3.4%	63.5%
SAU	4.100	2.8%	66.3%
CAN	4.000	2.8%	69.1%
QAT	3.048	2.1%	71.2%
FRA	2.600	1.8%	73.0%

Using the production data and global trade data of ammonia as described in the '*Input-output model development*' resulted in the outcomes presented in Table 3.

Table 3. *Estimated country of origin of the ammonia used in the different cement factories*

Plant I – CHN		*Plant II – EGY*		*Plant III – MYS*		*Plant IV – TUR*		*Plant V – DNK*		*Plant VI – BEL*	
Loc.	Per.	Loc.	Per.	Loc.	Per.	Loc.	Per.	Loc.	Per.	Loc.	Per.
CHN	100%	EGY	100%	MYS	99%	TUR	56%	DEU	84%	BEL	62%
				IND	1%	RUS	24%	NLD	6%	RUS	27%
						UKR	13%	POL	3%	TTO	3%
						DZA	3%	GBR	2%	NLD	3%
						EGY	2%	DZA	2%	UKR	1%
						BRA	1%	RUS	1%	USA	1%
						NGA	1%	BEL	1%	FRA	1%
						POL	1%				
						FRA	1%				

From the analysis it follows that all plants, except plant V, are mainly supplied with ammonia produced in their own countries. As such, trade tariffs or embargoes are unlikely to lead to supply chain disruptions for those plants. Plant V receives the ammonia from countries with a stable economic and political situation such as Germany and the Netherlands, as such not imposing a severe supply risk.

A next step could be to investigate the raw material supply to the ammonia plants, i.e. natural gas, to assess the risk of disruptions further upstream in the supply chain. Applying the input-output model on natural gas shows that the natural gas for the ammonia of plant I in China most likely comes from China (72%) or from Turkmenistan (13%). Like the Chinese plant, the ammonia supply to plant II in Egypt mainly relies on natural gas produced in the same country: Egypt (62%). However, Qatar is also a major supplier of natural gas to Egypt by accounting for approximately 16% of the total natural gas, while also small amounts of natural gas come from Algeria, Norway, The Netherlands and Nigeria. For plant III in Malaysia, the outcomes of the input-output model show that over 95% of the natural gas in Malaysia is produced in Malaysia itself. The same goes for Turkey, which does not rely on natural gas from other countries meaning that the supply of Turkish ammonia to plant IV is produced with Turkish natural gas. The other major ammonia suppliers to Turkey either rely on their own natural gas (Russia) or import around 25% of their natural gas from Russia (Ukraine). For plant V, the ammonia from Germany is produced with natural gas from Russia (44%), Norway (28%) and The Netherlands (19%). Finally, the natural gas in Belgium originates from a wide variety of countries: Norway (51%), The Netherlands (24%), the United Kingdom (11%), Qatar (9%) and Russia (4%).

Managers can use the insights into the origin of the ammonia and natural gas to make decisions on where (not) to invest in supply chain resilience, for example through increasing stock levels or purposely having a second source of ammonia for some factories.

4.2. Environmental and social risks: child labor in the cotton supply chain

The use of the input-output trade model to assess social risks is illustrated on the cotton supply chain. The cotton industry is notorious for its use of child labor and the environmental and social standards differ greatly between countries (Centre for Research on Multinational Corporations, 2014; United States Department of Labor, 2013). Uzbekistan is often considered the country with the most severe forms of child labor on the cotton fields. Uzbekistan's government, for example, forces children to harvest cotton (Kelly, 2017). Albeit sustainable certifications of cotton exist such as the Global Organic Textile Standard and Fairtrade, many producers somehow obtain certificates without complying to the required standards. Like many commodities, cotton is difficult to trace because cotton is mixed at trading points which opens the risk for environmental scandals in the supply chain configuration. We illustrate how the input-output model can give insights into how to avoid the use of cotton from countries such as Uzbekistan to reduce the chance of child labor in the supply chain configuration. The production data of cotton comes from the United States Department of Agriculture (2015).

Figure 3 provides insights into the outcomes of the input-output model of the cotton supply chain. The outcomes show that 44.9% of the cotton used in Russia is grown in Uzbekistan. Furthermore, large chunks of the cotton in Belarus (34.2%) and Latvia (13.4%) is grown on cotton fields in Uzbekistan. Hence, garment factories and other textile users located in those countries have a high risk of using cotton harvested by children in Uzbekistan. Other countries with more than 5% of their cotton coming from Uzbekistan's cotton fields are Moldova, Armenia, Lithuania, Poland and Kazakhstan, which might affect the choice of 'source-not source' or might increase the level of attention given by firms operating in these countries.

On the other hand, countries such as the USA and Australia have arguably less social and environmental sustainability issues. Table 4 shows an overview of the top 10 countries which source cotton from countries criticized for using child labor in their cotton production and the top 10 countries which use cotton produced in the USA or in Australia. Obviously, the risk of sustainable (child labor) scandals in the supply chain configuration is very different for cotton users located in those countries. These insights can be used to decide where to source cotton and products which contain cotton to avoid child labor in the supply chain or where to expend efforts and resources to control for occurrences of child labor in the supply chain configuration.

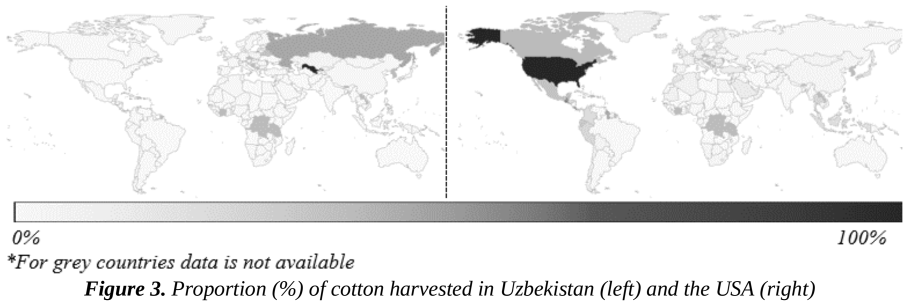

Figure 3. *Proportion (%) of cotton harvested in Uzbekistan (left) and the USA (right)*

Table 4. *Origin of the cotton per country*

Country	*Percentage from highly criticized countries**	*Country*	*Percentage from the USA or Australia*
Uzbekistan	100%	Australia	98.6%
Bangladesh	100%	USA	95.2%
India	96.5%	Dominican Rep.	68.0%
Pakistan	95.3%	Canada	37.7%
Sierra Leone	84.4%	Jamaica	37.2%
China	83.1%	Thailand	34.0%
Sri Lanka	82.9%	Mexico	32.2%
Gambia	82.3%	Ecuador	30.4%
Mauritania	81.5%	Indonesia	25.6%
Oman	80.0%	Singapore	23.3%

* The criticized countries are based upon reports of the Centre for Research on Multinational Corporations (2014) and the United States Department of Labor United Stated Department of Labor (2013) and include: Uzbekistan, India, China, Bangladesh, Egypt, Thailand and Pakistan. Other countries can be considered as well, depending on criteria for sustainability.

4.3. Enabling industrial symbiosis: sourcing of fly ash

To illustrate the use of the input-output trade model for the sourcing of byproducts, the case of fly ash is used. Fly ash is a byproduct of coal combustion and its suitability to produce low alkali cement depends on the alkali content of the fly ash. For the cement plant under investigation, only bituminous coal delivers suitable fly ash for cement production. The country of origin of the combusted bituminous coal has a large impact on the alkali content of the fly ash USGS (2016b).

According to USGS (2016b), the majority of bituminous coal is produced in South-Africa, Russia, Australia, Columbia and Indonesia while also some other countries produce smaller amounts of bituminous coal. Major ports such as Rotterdam and Hamburg often form hubs from where the coal is further distributed to the final destinations. Figure 5 provides an overview of the bituminous coal shipped to the Netherlands (mainly to the ports of Rotterdam and Amsterdam) and Figure 5 shows how the coal is redistributed to other countries. As evident from Figures 4 and 5, the information about coal origin for the coal trade after hubs like Rotterdam becomes blurred. The proposed input-output model is helpful to estimate the origin of the coal in the European market.

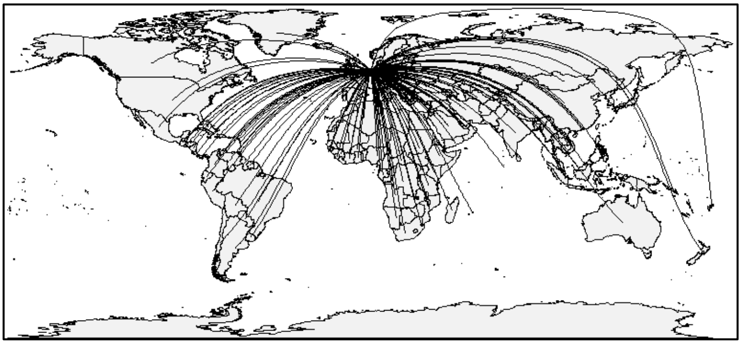

Figure 4. *Import of bituminous coal to the Netherlands*

Figure 5. *Export of bituminous coal from the Netherlands*

Using the input-output model, Figure 6 shows the percentages of Russian and South African coal per country. This serves as a proxy of the percentage of Russian and South African coal combusted in a given country. These insights provide cement manufacturers with initial clues on where to source fly ash. Obviously, other factors such as price, ease of accessing the fly ash (proximity to harbors or rail infrastructure) and market situation will affect the sourcing decision as well.

Figure. 6. *Proportion (%) of coal coming from South Africa (left) and Russia (right)*

Coal-fired power plants in France, Italy and Denmark were contacted to see how much South-African coal they combusted. In France and Italy, a relatively large amount of South African coal was found whereas in Denmark, the amount of South African coal seemed lower. This is in line with Figure 6, as such highlighting the use of the input-output model for the case of fly-ash.

5. Discussion

In this section, we discuss the limitations and weaknesses of using the presented input-output model. First, the analysis should be carried out within the framework of the entire supply chain network of a certain product, for otherwise the outcomes might be misleading.

Second, a country-level granularity allows to encompass various dimensions (political, legislative, industry practices, cultural, etc.) that shape the environmental and social sustainability performance of a product. Nevertheless, a finer granularity (e.g. region based) would be preferable, especially when countries are large (products sourced in the northern part of the United States might have a very different origin than the same product sourced in the southern part of the United States) or when the environmental and social performance between regions within the same country differs greatly.

Third, changes over time (in our case during the year, since the data of UN Comtrade is aggregated on a yearly basis) were left outside the scope of the model as only yearly data is currently available. As a result, the model is static. In case of a lot of smaller trades throughout the year, reality might be very different than the outcomes provided by the model. Hence, the model is less suitable for products which are traded frequently, and which are imported and exported various times before reaching the final market.

Fourth, the model assumes that the export is proportional to the import plus production of a country. Hence, local and foreign products have an equal ability to fulfil a similar demand. This might not always be the case. Foreign products may be imported to fulfill a special demand which is not fulfilled by domestic production.

Fifth, and lastly, the model presents an 'as is' snap representation of the real world. When firms act upon the model, for example by sourcing products in different countries, supply chain configurations might change accordingly. Nevertheless, small changes are unlikely to have large impacts on global supply chain configurations. Moreover, markets (on a country size) are often assumed independent from one another. Hence, an increase of demand on a market does not affect the level of demand in another market (Sacchi, 2017). The reasoning is the existence of long-term production and supply chain patterns which firms will not change when demand increases. E.g.: buying cotton in the US instead of Ecuador will increase the demand of cotton in the US. The firms based in the US will most likely use the same supply chains as they already do. The demand will therefore not go back to Ecuador (unless Ecuador already supplies to the US).

6. Conclusion

Based on trade data and Leontief's (1951) input-output approach, this paper presents a model which can be used to obtain insights into otherwise non-transparent supply chain configurations. From this, several practical implications can be derived. First, the model provides a starting point for deciding on how to make the supply chain resilient. Second, as shown in the case of cotton, the model can be used to assess the risk of child labor in supply chain configurations where CSR certificates fall short. Third, the model provides a starting point for environmental sourcing and sourcing in non-transparent byproduct markets. This research also contributes to literature, as we show the relevance of input-output modelling on creating transparency in supply chain configurations by using trade data to trace the origin of (intermediate) products. The transparency contributes to supply chain resilience, sustainable sourcing as well as the sourcing of waste and byproducts.

Nevertheless, we acknowledge that the presented model only provides a starting point for addressing risks in supply chain configurations. When supply chain configurations seem uncanny, other, more expensive, measures might be desired. Blockchain technology, for instance, might prove useful to create transparency and to trace the origin of (intermediate) products. Hence, future research is needed to examine the potential of blockchain technology in non-transparent supply chain configurations.

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PAPER III

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New environmental supplier selection criteria for circular supply chains: lessons from a consequential LCA study on waste recovery

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Although circular supply chains are widely perceived as a leap towards a more environmentally friendly economy, the environmental impact across circular supply chains differs. This article sets out to develop environmental supplier selection criteria for circular supply chains. The method draws upon a consequential life cycle assessment and the monetized environmental impact of four alternative fuel suppliers in the cement industry. The best supplier performs three times better than the worst supplier in terms of environmental impact, thereby exemplifying the need for this study. The findings also show how three supplier selection criteria explain most of the environmental impact of selecting a supplier in a circular supply chain. First, supplier selection might impact environmentally preferred waste handling activities. Second, sourcing from a supplier located on an under-supplied market may lead to indirect transport as the players on that market may source on other markets to compensate for the diverted products. Third, low usability of the discarded product compared to the substituted virgin material may lead to additional emissions. The three criteria must be considered simultaneously when selecting suppliers in circular supply chains since focusing on a single criterion may negatively affect the other criteria. The findings contribute to circular supply chain literature by proposing and demonstrating the need for environmental supplier selection criteria in circular supply chains. Moreover, this study is relevant for achieving cleaner production in the cases where firms increasingly rely on the use of discarded products as a virgin fuel or material substitute.

1. Introduction

While firms experience a pressing need to engage in the circular economy, the link between circular economy and sustainability remains blurred (Geissdoerfer et al., 2017). Concrete examples of the pressing need include the Circular Economy Production Law of the People's Republic of China (The Standing Committee of the National People's Congress China, 2008) and the European Circular Economy package (European Commission, 2015). Concurrently, Wolfenbarger and Phifer (2000) stress the complex and ambiguous nature of environmental impacts. Selecting suppliers based on environmental performance therefore becomes a complicated task (Bai and Sarkis, 2010; Matos and Hall, 2007). Hence, academics and practitioners alike consider supplier selection criteria (SSC) as a valuable means to select suppliers (Bai et al., 2012). While literature offers environmental SSC (E-SSC) for forward supply chains – see for example Freeman and Chen (2015) – literature lacks E-SSC for circular supply chains (Wells and Seitz, 2005).

Forward supply chains differ significantly from circular supply chains. Circular supply chains source on markets where the availability of a discarded product (e.g. used tin cans) is constrained by the demand for the primary product it originates from (e.g. canned food). Households and firms do not discard more products when the demand for discarded products increases. Besides, waste handling activities in circular supply chains are mutually exclusive. For example, the recycling of a discarded product excludes its incineration or landfilling. The combination of constrained supply and mutually exclusive waste handling activities leads to a situation where an increase in demand for a supplier of discarded products creates a supply shortage for other waste handling activities, including landfilling.

Creating shortages at other waste handling activities affects the environment. First, not all the waste handling activities are equally efficient at recovering value from discarded products (Mondragon et al., 2011; Schmidt et al., 2007). Diverting discarded products from a less eco-efficient waste handling activity has a positive environmental impact; diverting discarded products from a more eco-efficient waste handling activity has a negative environmental impact. Second, transport-related emissions increase when waste handling activities start to import discarded products to compensate for the created shortage. In addition, the environmental impacts related to the processing of discarded products should be taken into account as well (Geng et al., 2012). This study therefore aims to develop generic E-SSC for circular supply chains by considering the constrained nature of the supply, the competition of waste handling activities for discarded products as well as the processing of the discarded products in the receiving production system.

To achieve this aim, a consequential life cycle assessment (CLCA) is conducted to assess the environmental impact of selecting different municipal solid waste (MSW) suppliers in the cement industry. CLCA is a particularly well-fitting tool for this study as it characterizes the changes in the economic system related to an increase in demand for a product. Hence, CLCAs can be modeled to consider the supplier's reaction to demand and supply changes at the margin. This is crucial when the product under investigation is constrained in supply and system-wide impacts may occur – as is the case in circular supply chains. Therefore, E-SSC based on a CLCA adhere to the suggestions of Seuring and Müller (2008) to include environmental impacts beyond the immediate interfaces of the supply network.

Despite the interests of policy makers and firms into the circular economy (Geng and Doberstein, 2008; Ghisellini et al., 2015; Lieder and Rashid, 2016), how firms can environmentally optimize their circular supply chains remains unclear (Geissdoerfer et al., 2017). Therefore, this study contributes to literature by proposing E-SSC for circular supply chains. The proposed E-SSC offer guidelines that firms can follow to achieve cleaner production and increase the environmental performance of their circular supply chain activities. Moreover, the E-SSC support the design of policies by providing insights into preferred circular supply chain efforts. Finally, this study contributes to literature by demonstrating the need and relevance of the proposed E-SSC for the use of MSW in the cement industry.

This article is organized as follows. It begins with the review of the supply chain literature on E-SSC and subsequently explore E-SSC for circular supply chains. It then presents the methodology and demonstrates the need, applicability and underlying mechanisms for E-SSC based on a case study of the use of the combustible fraction of MSW in the cement industry. It eventually concludes the article with a discussion of the results followed by a conclusion.

2. Literature Review

The real world complexity related to supplier selection creates the need for simplified but thoughtful SSC (Govindan, et al., 2015; Williamson, 2008). The complexity increases even more when adding environmental aspects (Bai and Sarkis, 2010). It is therefore not surprising that E-SSC have attracted growing interest in literature and practice (Bai et al., 2012).

Most E-SSC presented in literature set out to screen suppliers in the forward supply chain based on their *organizational* performance, e.g. complying with ISO standards or green product design. Table 1 provides an overview of the most frequently used E-SSC in literature. Although some E-SSC touch upon aspects of circular supply chains – e.g. product design for reuse – existing E-SSC do not consider the constrained supply of discarded products and the mutual exclusiveness of waste handling activities. The next paragraphs elaborate on why circular supply chains require different E-SSC.

Table 1
Frequently used E-SSC in literature (based on Bai and Sarkis, 2010; Freeman and Chen, 2015; Govindan et al, 2013; Handfield et al., 2002; Lu et al., 2007; Zhu and Sarkis, 2004).

Organizational aspects	Related attributes
Product design	Product design for reuse, recycle and recovery of material; green packaging; excess package reduction; toxic and hazardous components.
Process design	Internal recycling at the supplier; use of recycled materials; waste water; solid waste; energy consumption; resource consumption; air pollutants; emission and release of harmful substances.
Environmental management systems	ISO 14001; end-of-pipe control; eco-labeling; continuous monitoring; regulatory compliance; green process planning; up-to-date air, water and pollution permits.
Miscellaneous	Management commitment; environmental performance of the suppliers' supplier; staff training on environmental issues; ability to improve towards more environmental activities; social responsibility.

2.1. The distinct context of circular supply chains

Circular supply chains include forward supply chains and reverse activities (Wells and Seitz, 2005). The reverse activities of circular supply chains include (Tibben-Lembke and Rogers, 2002):

- Collection of waste / end-of-life products, hereinafter referred to as discarded products,
- Reverse logistics,
- Quality assessment, and
- Recycling, remanufacturing and other forms of recovery or disposal.

This research focuses on the reverse activities because ample research already addresses E-SSC for forward supply chains (Govindan et al., 2015). Literature distinguishes two types of circular supply chains. First, closed-loop systems aim to return products to their point of origin. Examples include Xerox's copy machines and Kodak's cameras. Second, in open-loop systems, other parties rather than the original producers recover the value of the discarded products. Examples include recycling firms and the exchanges taking place within industrial symbiosis networks: where waste and by-products of one firm serve as feedstock for another firm (Chertow, 2000). The next sections elaborate on how the environmental performance of both types of circular supply chains hinge on two key characteristics, namely 1) the constrained supply- and demand-driven product flows and 2) the usability of discarded products.

2.1.1. Product flows in circular supply chains

Circular and forward supply chains have different product flows (Tibben-Lembke and Rogers, 2002). Forward supply chains extract virgin materials to respond to customer demand. When customer demand increases, virgin material extraction increases (Naylor et al., 1999). Hence, forward supply chains have demand-driven product flows and are unconstrained in supply as long as virgin materials are available. In contrast, circular supply chains fulfill customer demand by extracting the remaining value of discarded products and looping them back into the economy (de la Fuente et al., 2008). As such, the supply of discarded products is constrained by the consumption of the primary product it derives from (Ekvall and Weidema, 2004). At the same time, like in forward supply chains, customers may dictate the demand for discarded products, as such leading to demand-driven product flows. Only when discarded products leave the circular loop and enter landfills and waste incineration without energy recovery, the product flows become supply-driven. Figure 1 provides an overview of the constrained supply and the demand and supply-driven product flows in circular supply chains. The next paragraphs elaborate on how the constrained supply and the demand and supply driven product flows of discarded products affects the environmental impact of circular supply chains.

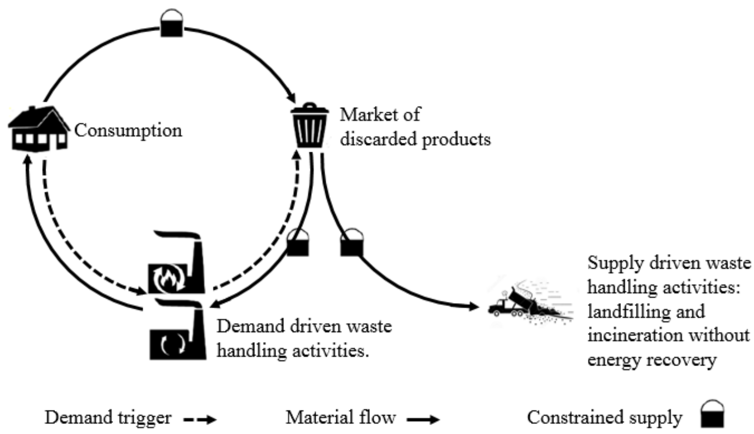

Fig. 1. The constrained demand and supply driven product flows in circular supply chains.

2.1.2. Induced transport

The constrained supply of discarded products may lead to inter-market trade and transport operations. When a firm increases its intake of discarded products, the other waste handling activities who operate on the same market may fall short of discarded products. In response, the short-falling waste handling activity may source discarded products from a market located in a different geographical area. The subsequent increase in demand experienced on the other market may, in turn, create a shortage for the waste handling activities operating on this market. This ricochet effect continues until the demand in all involved markets is satisfied; this happens when the chain of trade reaches an *end-market.* An end-market satisfies the newly expressed demand while meeting its own domestic demand for discarded products. End-markets either have an abundant supply of discarded products (which might otherwise be absorbed by supply-driven activities such as landfills or incinerators without energy recovery) or replace the missing discarded products with virgin materials (e.g. use of natural gas to compensate for the lack of MSW on the district heat market). The transport that occurs because of the above-described situation can be divided into direct and indirect transport. *Direct* transport refers to the transport between the buyer and the first-tier supplier. *Indirect* transport refers to the transport following the trade operations between different geographical markets.

Previous research shows how transport which occurs beyond the first-tier in a supply network has an environmental impact. For example, Sim et al. (2007) show that (in)direct transport can play a major environmental role when selecting a supplier in the forward food supply chain, with transportation sometimes cancelling out the benefits of preferred food production methods. Likewise, Xing et al. (2016) and Tasca et al. (2015) argue that transport emissions depend on the selected supplier and the transport occurring in the supplier's upstream supply chain. Liotta et al. (2015), Sundarakani et al. (2010) and Wang et al. (2011) show how changing the first-tier supplier may reduce the environmental impact of transport. As selecting a supplier for discarded products may trigger a chain of trade, E-SSC for circular supply chains should also consider the environmental burden of both direct and indirect transport. Unfortunately, the aforementioned studies focus on forward supply chains rather than circular supply chains. Therefore, the impact of indirect transport in circular supply chains remains unclear and requires further investigation.

2.1.3. Affected waste handling activity

The affected end-market determines the affected waste handling activity. The identification of the affected waste handling activity that runs short of supply is sensitive to the long-term expanding or decreasing nature of the end-market. Weidema et al. (1999) argue that an increase in demand on an expanding market (i.e. the increasing availability of discarded products) affects the marginally most-preferred waste handling activity – i.e. the waste handling activity which processes more discarded products over time. The opposite logic holds also true: a decrease in demand on a declining market affects the least-preferred waste handling activity.

The affected waste handling activity influences the environmental performance of circular supply chains as processing a discarded product in one way avoids its processing by another waste handling activity. In general, the waste hierarchy provides an environmentally preferred way of action (Moberg et al., 2005; Schmidt et al., 2007). The waste hierarchy favors waste handling activities which take advantage of the usability and residual value of discarded products. Moberg et al. (2005) argue that waste processing leads to a lower environmental burden when *disposal < energy recovery < recycling < reuse < reduction < prevention*. To determine the environmental performance of both open-loop and closed-loop circular supply chains, firms should consider which waste handling activity runs short of supply when they express a demand for a given discarded material.

2.1.4. Usability of discarded products

The extent to which discarded products fulfill the function of the substituted virgin materials – a concept coined *usability* in this study – may affect the environmental performance of circular supply chains in several ways. First, discarded products may have a lower quality than their virgin counterparts. For example, MSW may have a lower heating value than fossil fuels and recovered fibers may have a lower flexural strength than virgin fibers. A lower usability may increase the number of discarded products needed to substitute a given virgin counterpart. This may lead to increased transport and diverting more material from other waste handling activities. Second, discarded products may require additional processing such as disassembling, cleaning, melting and quality checks (Guide et al., 2003). These additional processing activities may have an impact on the environment (Chen et al., 2010; Fijał, 2007). Third, in industries with capacity constraints – such as process and capital-intensive industries – the production output may decrease when the use of discarded products hampers production efficiency (Prosman et al., 2017). To keep a constant output, other firms (with varying environmental performances) may have to produce and transport the missing products.

The impact of the constrained supply and demand driven circular supply chains as well as the impact of the usability of the discarded products as explained above are not reflected in E-SSC found in the literature (see also Table 1). The novelty and relevance of this study is to propose a set of E-SSC for circular supply chains and demonstrate their need. The proposed E-SSC can help firms to progress towards sustainable societies by offering cleaner products and by substituting virgin resources with discarded products. In addition, the proposed E-SSC can serve as guidelines for policy makers.

3. Method

A CLCA based on an in-depth single case study in the cement industry serves to empirically investigate E-SSC for circular supply chains (Eisenhardt, 1989). Matos and Hall (2007) qualify CLCA as a comprehensive analytical tool and justify its use to quantify the environmental impacts of supply chain operations following an increase in demand for a given product or service, such as discarded products. In line with the research goal, performing a CLCA based upon a case study allows to obtain a thorough understanding as the approach mobilizes multiple observations and draws in the significance of various interconnected levels of sustainability related to supplier selection within circular supply chains. The study relies on the case of a cement factory (CEFA). CEFA, one of the largest cement factories in Europe, consumes vast amounts of energy and experiences severe pressures to reduce its environmental impact. As such, CEFA gradually replaces fossil-based fuels such as coal and petroleum coke with refuse-derived fuel and specified recovered fuel, both referred to as combustible waste (CW). CW is the combustible residual waste fraction obtained from the processing of MSW by materials recovery facilities (MRFs) after taking out precious materials (e.g. metals and uncontaminated plastics for the scrap market).

CEFA's CW supply chain offers fertile ground to explore supplier selection issues in circular supply chains. First, CW may lead to indirect transport when procured on an undersupplied market. Second, using CW for cement production affects other waste handling activities, namely landfilling and incineration with and without energy recovery. Third, the usability of CW – mainly determined by energy, moisture and chloride content – results in a lower fossil-fuel substitution rate and increased transportation, handling operations and production losses. As CEFA's CW supply chain presents all the identified supplier selection issues presented in the literature review, researching the CW supply chain allows to obtain in-depth and system-wide insights.

The CLCA study has been performed according to the principles and recommendations listed in the ISO 14040:2006 (ISO, 2006) and 14044:2006 (ISO, 2006b) standards with the LCA software *OpenLCA*. The study follows the following steps:

1. Formulation of the goal and scope of the study: the functional unit in terms of energy input to produce one ton of Portland cement, to be fulfilled with CW;
2. Determination of the system boundaries of the analysis: the limits of the studied system between the cement factory and its suppliers;

3. Definition of the product system and its inventory: the material and energy input and output flows within the product system as well as the impacts of the introduction of CW on the productivity and emissions of the cement kiln;
4. Organization of the different European waste markets and the modelling of the effects associated to CW supplier selection;
5. Characterization and monetization of the environmental impacts associated to supplier selection: the resulting inventory for each scenario is solved and characterized against a set of impact categories and monetized to obtain an aggregated environmental cost figure;

The steps are discussed in more detail in the next sections.

3.1. Goal and scope

The goal of the CLCA study is to model the changes in the economy that relate to the realization of a functional unit: the production at the margin of one ton of clinker by using CW instead of petroleum coke. Clinker is the main binding ingredient in cement which is ground and mixed with approximately 3% of gypsum to form cement. The model iterates through four different CW suppliers and characterizes the mechanisms underlying the environmental impacts to derive E-SSC for circular supply chains.

As the focus is on the environmental consequences of supplier selection in circular supply chains, the adopted scope is "cradle-to-production".

3.2. System boundaries

The definition of the product system excludes the "production-to-gate" activities such as milling of cement, transportation to end-users and the subsequent use, as the environmental performance of these activities is not affected by a shift in fuel types. Likewise, except for the need for additive materials due to the shift to CW, the provision of raw materials for clinker is excluded to isolate the environmental burden linked to selecting a certain CW supplier. Moreover, the upstream activities associated to the waste generation (i.e. the forward supply chains where the primary materials the CW derives from) are not accounted for, since, as discussed in the literature review, an increase in demand for CW does not lead to an increased amount of generated and collected discarded products (Ekvall and Weidema, 2004). The model accounts for the direct transport of CW to the cement plant, the indirect transport of CW between CW markets to supply the displaced demand, the affected waste handling activity on the end-market (avoided landfilling, avoided incineration and forced heat production) and the usability of the CW.

MRFs source material on the MSW market and supply recycling, incineration (with or without energy recovery) and landfilling activities after cleaning and sorting the material. Sending material to the landfill often represents a cost rather than an income for MRFs. Hence, landfills usually receive the MSW which has not been absorbed by the other waste handling activities. Likewise, since recycling has a higher economic return than CW, an increase in demand for CW does not affect recycling. An increase in the demand for CW may affect the waste handling activities which do not economically outperform CW and which compete for the same discarded products (e.g. landfill and incineration with or without energy recovery).

As shown in Fig. 2, when CEFA increases the demand for CW, denoted by $+\alpha$, the amount of CW available for other waste handling activities in the target market shrinks. The supplying market may react by 1) diverting CW from other waste handling activities (an end-market), 2) using a virgin substitute (an end-market) or 3) by importing CW from one or several markets that have a marginally increasing export with the supplying market. A series of trade transactions occur until an end-market is reached (a market that only exports CW), denoted by indirect transport in Fig. 2.

In the case of an end-market with a declining availability of CW, the least-preferred waste handling activity will be affected, denoted by $-\alpha$ in Fig. 2. In contrast, on end-markets with an increasing amount of available CW, the marginally most-preferred waste handling activity is affected. If a demand-driven waste handling activity is affected (e.g. waste incineration with energy recovery), the affected market (e.g. the district heat market) uses an alternative supply (e.g. natural gas-fired heat plant) to keep its output constant. If a supply-driven waste-consuming activity is affected (e.g. landfill), the latter simply reduces its output by an equivalent amount (i.e. amount of material landfilled).

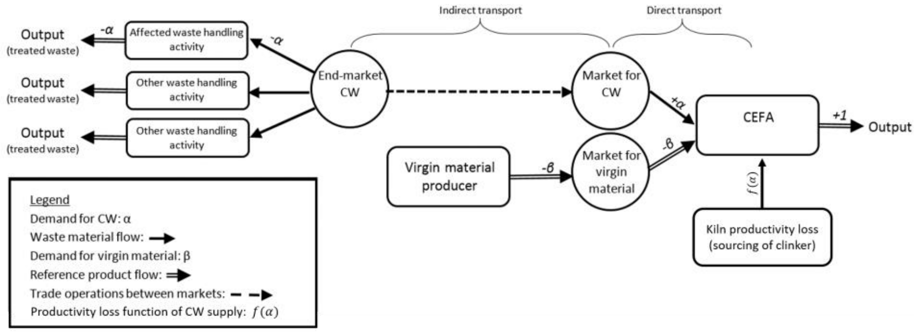

Fig. 2. Illustration of the system boundaries of the shift in demand from virgin material to waste material.

3.3. Inventory analysis

To obtain rich data, the data collection involves a combination of qualitative and quantitative data (Yin, 2013). Data over a one-year period is collected where the day-to-day involvement of the authors augmented a comprehensive and rich understanding of the relevant inputs and outputs in clinker production. The data collection covered two distinct areas: 1) supply chain system boundaries and 2) environmental impacts. For both areas, multiple data sources are used, including archival and supplemental data to increase construct validity (Voss et al., 2002).

3.3.1. Data

Table 2 provides an overview of the data sources. At the cement factory level, the four types of CW were analyzed in a laboratory to obtain information on their physical properties (moisture content, fossil/biogenic carbon content, lower heating value, density, ash content). Clinker production data series were extracted from the monitoring software of CEFA. This data allowed to model the kiln behavior based on the fuel input such as the changes in kiln emissions and the impacts on the kiln productivity for each type of CW introduced. Interviews with the personnel of the supply chain and procurement functions of CEFA helped to model the way the conventional fuels and CW are supplied (origins of supply, distances and modes of transport). The LCI database ecoinvent 3.2 (consequential version) was used for the logistics-related background processes. Visits of the CW suppliers gave an understanding of how the CW markets work and how the MRFs react to an increase in demand for CW (and what the affected markets are when demand increases). Eurostat data series on the generation and trade of MSW over time helped to model the reaction of European markets to changes in demand for MSW. As explained in detail in the section *Scenario description*, it was possible to identify the marginal supply route for CW for each country given the trend of the domestic MSW market (annual quantities available and how they are absorbed by the different waste handling activities) and its position in the MSW trade network. Finally, Ecoinvent was again used to model the avoided waste handling activities.

Table 2
Data sources.

Area	Data sources	Purpose
Supply chain system boundaries definition	- Interviews with supply chain and purchasing managers of CEFA - Supplier visits - Archival sources (supplier audits and market research outcomes) - Eurostat (2013) MSW trade data - CEFA's ERP system	Defining the system boundaries: available suppliers, CW flows, types of CW.
Inventory modeling	- Laboratory analyses* - Supplier visits and interviews - Transportation data (incl. mode of transport) - Production data, Ecoinvent 3.2	Determining fossil carbon emissions; physical and energy inputs and outputs; the avoided emissions from waste handling alternatives; emissions related to transport; avoided emissions associated to the avoided use of virgin materials.

* Carbon14 analyses were conducted to determine the biogenic carbon share for each CW material. Various other analyses were conducted to determine the CW usability: LHV, moisture, ash and chlorine content, etc.

3.4. Scenario description

MSW generation and treatment data as well as the registry of transboundary shipping of waste (European Waste Code *19 12 10* - refuse-derived fuel) provided by Eurostat (2013) allowed to model the 28 national MSW markets in Europe. Based on the data, MSW markets are grouped into three categories:

- *Import-only markets*: characterized by a CW handling capacity superior to the domestic CW generation.
- *Import-export markets*: they adjust their domestic demand for CW by importing and exporting.
- *Export-only markets* (or end-markets): characterized by a structural lack of waste handling capacity compared to the domestic CW generation (usually with a late ban on landfill of organic waste and an insufficient thermal treatment capacity).

The traded amount of MSW between the MSW markets allowed to estimate the indirect transport between the MSW markets. A time horizon of 5 years is used to determine the marginally-preferred import markets for each market. Fig. 3. illustrates the trade transactions following an increase of demand for CW by one ton on the Swedish market. The involved markets eventually return to an equilibrium between supply and demand when end-markets provide the missing amount of CW. In this case, Norway and the United Kingdom provide most of it (as well as, to a lesser extent, Poland, France, Italy, Luxemburg and Ireland). Note that the overall amount of additional CW exceeds the initial increase in demand because the lower heating value on each MSW market differs. For instance, the trade-ability between one ton of CW from Sweden and one ton of CW from Germany is not a one-to-one ratio (the former has a higher average lower heating value).

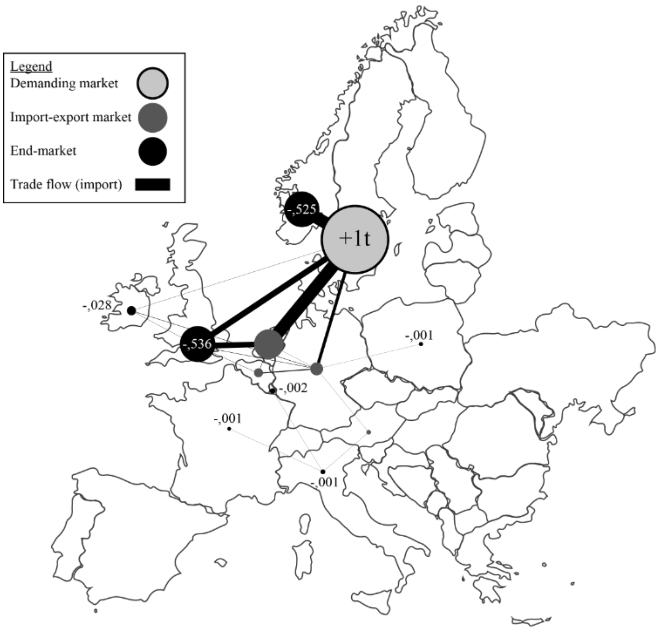

Fig. 3. Waste trade supply following an increase of demand of one ton for CW on the Swedish market.

Table 3 lists different MSW markets, their respective category and the markets y trade with, based on Eurostat's MSW utilization and trade data for the European Waste Code *19 12 10* (refuse-derived fuel). The lower heating value of the MSW is used as the determining property and function of the material flow, rather than its mass. A time horizon of 5 years has been used to determine the volume trend and the affected waste handling activity.

Table 3
Examples of modelled waste markets.

Market location	Market category	Marginal import markets	Volume trend	Affected waste handling activity	Average lower heating value (MJ/Kg)
Germany	Import-export	IR, AU, FR, NL, PL, LUX, BE, GB, IT	Increasing	n/a	10.1
Norway	Export only	n/a	Increasing	Waste CHP with energy recovery	11.7
Ireland	Export only	n/a	Decreasing	Landfill	9.7
Denmark	Import only	DE, IR, NO, NL, GB	Increasing	n/a	11.7

Finally, four different MRFs – potential CW suppliers to CEFA – are considered. Table 4 provides an overview of the main characteristics of each CW supplier under investigation. Material properties such as the lower heating value, moisture content and variation in the lower heating value are important parameters in the estimation of productivity losses in CEFA's production set-up. These properties ultimately determine the usability of the CW. Biogenic/fossil carbon content and (in)direct transport means and distance are used to calculate emissions linked to the supply and combustion of the CW.

Table 4
Supplier characteristics: location, material characteristics and modes of transport.

Supplier	Location	Lower heating value (MJ/Kg ww)	Moisture (% ww)	Biogenic carbon (% ww)	Direct transport (ton-km)	Mode of transport
A	Germany	23.8	17.9	19.3	566	Ship
B	Sweden	27.2	1.2	31.2	294	Ship/truck
C	Great Britain	15.4	17.6	20.5	1112	Ship/truck
D	Denmark	34.6	15	0	282	Ship/truck

3.5 Impact assessment

The impact characterization method StepWise2006 v1.5 is used to assign environmental impacts to the calculated inventory. The StepWise2006 method relies on established impact assessment models (IMPACT2002+ and $EDIP_{2003}$) to assess potential impacts in regard to categories such as global warming, respiratory organics and inorganics, eco-toxicity, nature occupation, human-toxicity, eutrophication, acidification, mineral extraction and ozone layer depletion (Weidema, et al., 2007). Previous research found that these have a predominant impact on circular supply chain systems (Schmidt et al., 2007), as such rendering StepWise2006 an appropriate method. For ease of comparison between the supply scenarios, the StepWise2006 method offers the possibility to monetize the environmental impacts to provide a single aggregated environmental costs figure which includes the different impacts, expressed in $Euros_{2003}$ (the value of the currency in 2003, used in StepWise2006) (Weidema, 2015). Table 5 presents the list of monetizing factors used by StepWise2006. See Weidema (2015) and Weidema (2009) for further information on the development of StepWise2006 and impacts monetization.

Table 5
Monetization factors used by StepWise2006.

Impact factor	Unit	Monetization factor
Nature occupation	$Euro_{2003}/m^2$-year of agricultural land	0.124
Mineral extraction	$Euro_{2003}$/extra MJ needed	0.0041
Human toxicity, non-carcinogens	$Euro_{2003}$/kg C_2H_3Cl-eq	0.2712
Global warming, fossil	$Euro_{2003}$/kg CO_2-eq	0.083
Respiratory inorganics	$Euro_{2003}$/person*ppm*hour	67.602
Human toxicity, carcinogens	$Euro_{2003}$/kg C_2H_3Cl-eq	0.264
Eco-toxicity, aquatic	$Euro_{2003}$/kg TEG-eq	7.4E-6
Photochemical ozone, vegetation	$Euro_{2003}/m^2$*ppm*hour	3.71E-4
Acidification	$Euro_{2003}/m^2$ of unprotected ecosystems	0.0077
Ionizing radiation	$Euro_{2003}$/Bq C-14-eq	2.0E-5
Eco-toxicity, terrestrial	$Euro_{2003}$/kg TEG-eq	11.05E-3
Ozone layer depletion	$Euro_{2003}$/kg CFC-11-eq	103.11
Eutrophication, aquatic	$Euro_{2003}$/kg NO_3-eq	0.1014
Respiratory organics	$Euro_{2003}$/kg PM 2.5-eq	0.26
Eutrophication, terrestrial	$Euro_{2003}/m^2$ of unprotected ecosystems	0.0124

4. Results and discussion

Table 6 shows the overall environmental impact following an increase of demand for CW from each supplier to produce one ton of clinker for Portland cement. The impact categories ‘global warming’ and ‘respiratory inorganics’ explain most of the overall characterized impact. The shift from petroleum coke to CW explains most of the avoided emissions of greenhouse gases. The increased transportation explains most of the emissions that contribute to human and ecosystem toxicity. As evident from Table 6, increasing the demand for CW from any of the four suppliers leads to a net environmental improvement due to fossil fuel substitution. Nevertheless, the environmental impact of supplier selection differs significantly: selecting supplier C leads to an environmental improvement almost four times larger than selecting supplier B.

Table 6
Environmental cost per impact category of producing one ton of clinker with CW instead of petroleum coke. Negative figures indicate that avoided impacts (related to the combustion of petroleum coke) are larger than occurring impacts (related to the combustion of CW). Unit: $Euro_{2003}$.

Impact factor	**Supplier A**	**Supplier B**	**Supplier C**	**Supplier D**
Nature occupation	0.228	1.166	-0.099	0.247
Mineral extraction	0.005	0.019	0.000	0.005
Human toxicity, non-carcinogens	0.550	0.266	0.591	0.495
Global warming, fossil	-20.695	-15.138	-25.521	-15.253
Respiratory inorganics	3.666	5.186	-0.773	1.619
Human toxicity, carcinogens	0.212	0.046	0.324	0.202
Eco-toxicity, aquatic	0.013	-0.010	-0.004	0.001
Photochemical ozone, vegetation	-0.476	-0.134	-0.598	-0.479
Acidification	0.002	0.041	-0.018	-0.004
Ionizing radiation	-0.005	-0.020	-0.005	-0.010
Eco-toxicity, terrestrial	1.115	0.838	0.047	0.578
Ozone layer depletion	0.000	0.000	-0.001	-0.001
Eutrophication, aquatic	-0.085	-0.041	-0.087	-0.078
Respiratory organics	-0.045	-0.016	-0.050	-0.043
Eutrophication, terrestrial	0.079	0.098	-0.022	0.032
Total	**-15.436**	**-7.699**	**-26.216**	**-12.689**

Table 7 shows that the E-SSC of transportation, the affected waste handling activity and the usability of the discarded products explain most of the difference in environmental impact between the CW suppliers. The last column of Table 7 shows that the environmental cost of CW supplier selection differs with 9.06, 10.35 and 6.65 $Euro_{2003}$ for transport, the affected waste handling activity and the usability respectively. Remaining operations, e.g. the sorting and cleaning of waste, only explain a minor share of the environmental impact of selecting suppliers in CEFA’s circular CW supply chain.

Table 7
Environmental cost per E-SSC of producing one ton of clinker with CW instead of petroleum coke. Negative figures indicate avoided impacts. Unit: $Euro_{2003}$.

	Supplier A		**Supplier B**		**Supplier C**		**Supplier D**		**Max. diff.**
Env. cost of avoided petroleum coke combustion	-23.28		-23.28		-23.28		-23.28		
Env. cost of avoided petroleum coke transport	-4.10		-4.10		-4.10		-4.10		
Total of avoided env. cost		*-27.38*		*-27.38*		*-27.38*		*-27.38*	*0*
Env. cost of direct truck transport	0.00		0.41		0.82		0.05		
Env. cost of direct ship transport	0.25		0.08		0.62		0.09		
Env. cost of indirect truck transport	9.63		5.47		0.00		4.93		
Env. cost of indirect ship transport	0.62		0.86		0.00		0.66		
Total env. cost of transport		*10.50*		*6.82*		*1.44*		*5.73*	*9.06*
Env. cost of avoided landfill	-12.46		-6.37		-11.94		-11.10		
Env. cost of avoided waste CHP	0.79		4.78		0.00		1.08		
Total env. cost of affected waste handling activity		*-11.67*		*-1.59*		*-11.94*		*-10.02*	*10.35*
Env. cost of lost productivity	2.38		1.84		3.93		2.00		
Env. cost of CW combustion	10.38		12.94		8.42		16.56		
Total env. cost of usability		*12.76*		*14.78*		*11.81*		*18.46*	*6.65*
Remaining env. cost		*0.35*		*-0.33*		*-0.15*		*0.42*	*0.75*
Total env. cost		***-15.44***		***-7.70***		***-26.22***		***-12.69***	***18.52***

4.1. Transportation

Supplier selection has a significant impact on transport emissions in CEFA's circular CW supply chain. A major share of the transport ensues from indirect transport due to inter-market trade – see Table 8. The long distance between supplier C and CEFA explains the high emissions due to direct transport. Nevertheless, the position of supplier C on an end-market prevents indirect transport. In contrast, emissions related to the indirect transport following the selection of supplier A, B and D surpass the emissions related to the direct transport following the selection of supplier C. This is due to inter-market trade. This finding resembles the findings of, amongst others, Xing et al. (2016) and Tasca et al. (2015). These authors argue that transport emissions (partly) depend on the selected supplier and the indirect transport in the supplier's upstream supply chain. CEFA's circular supply chain shows that circular supply chains may have emissions due to indirect transport too, caused by the constrained nature of supply. Therefore, firms should consider both direct and indirect transport when selecting suppliers for discarded products. The proximity of the supplier to an end-market may serve as an indicator of indirect transport.

In addition, the emissions depend on the mode of transport. In general, ship transport environmentally outperforms road transport (Spielmann et al., 2007). The findings show that emissions associated to direct transport following the selection of supplier C are kept relatively low due to the reliance on ship transport. In contrast, emissions associated to indirect transport following the selection of supplier A are relatively high due to the dominant use of trucks.

Table 8
Direct and indirect transport operations and trade. Negative figures indicate that avoided transportation requirements (related to the substitution of conventional fuel) are superior to occurring transportation requirements (related to the supply of CW).

Supplier	**Affected market**	**Direct transport [ton-km]**		**Indirect transport [ton-km]**		**Involved markets 1st order trade***	**Involved markets 2nd order trade***	**Involved markets 3rd – nth order trade***
		Truck	Ship	Truck	Ship			
A	DE	0.0	62.5	204.7	154.5	BE, NL, GB, IR, AT, PL, IT, FR, LUX	NL, DE, LUX, FR, GB, IR, IT	DE, NL, LUX, FR
B	SE	8.7	20.8	116.3	215.1	NL, NO, GB, DE, IR	GB, BE, IR, DE, NL, AT, PL, FR, IT, LUX	IT, DE
C	GB	17.4	155.6	0.0	0.0	-	-	-
D	DK	1.2	19.5	104.8	163.8	GB, DE, IR, NO, NL	BE, NL, GB, IR, AT, PL, FR, IT, LUX, DE	NL, DE, LUX, FR, IT

*** Underlined countries are end-markets, no further trade occurs from this point.**

4.2. Affected waste handling activity

The selection of a supplier eventually affects waste handling activities located on the end-market. In the case of CEFA, sourcing CW leads to either diverting CW from landfills or waste-fired CHP plants. Table 9 shows the affected waste handling activities for supplier.

In line with Moberg et al. (2005) and Schmidt et al. (2007), the results show that the environmental impact of the affected waste handling activity follows the order of preference given by the waste hierarchy. Diverting CW from landfills to use it for the higher-ranked energy recovery translates in a net environmental improvement. Reducing the need for depositing CW in landfills avoids greenhouse gas emissions and the release of leachates in ground and surface water compartments. In contrast, diverting CW from thermal treatment with energy recovery may lead to an increased use of conventional fuels (e.g. natural gas) of local heat suppliers to respond to energy demands. Hence, when selecting suppliers in circular supply chains, firms should consider which waste handling activity they affect to estimate the net environmental impact.

Table 9
Affected waste handling activities per supplier.

Supplier	Initial demand of CW [Kg]*	Landfilled, GB [Kg]**	Landfilled, PL [Kg]**	Landfilled, IR [Kg]**	Landfilled, IT [Kg]**	Used in waste CHP, FR [Kg]**	Used in waste CHP, NO [Kg]**	Used in waste CHP, LUX [Kg]**
A	122	-213	-5	-31	-8	-3	0	-8
B	107	-125	0	-6	0	0	-122	0
C	189	-248	0	0	0	0	0	0
D	84	-188	0	-40	-1	0	-25	-1

* Amount of CW required to fulfill the energy input target of 695 MJ
** Amounts of waste material used by different waste handling activities on end-markets, in Kg. Negative inputs translate as avoided/diverted. The sum of waste diverted from these activities may surpass the initial demand in Kg, since the trade-ability of CW is in reference to its lower heating value, not mass.

4.3. Usability

Differences in usability between the supplied CW affect the environmental performance of circular supply chains – see Table 10. There are several reasons why poor usability of CW results in additional emissions – mostly an increase of global warming and respiratory inorganics related impacts. First, the low usability caused by a low lower heating value means that CEFA must combust larger amounts of CW to replace the same amount of fossil fuels. Thus, the extent to which discarded products substitute the function of their virgin counterparts affects the environmental performance of the circular supply chain. Second, a high share of fossil-based carbon content in the CW affects the usability as it results in increased emissions of fossil-based CO_2 – short-termed biogenic-based CO_2 emissions are not characterized by StepWise2006. Moreover, production inefficiencies related to the moisture content of CW and variation in lower heating value reduce CEFA's production capacity. CEFA sources clinker elsewhere to fulfill the demand for clinker which leads to emissions of greenhouse gas and particulate matter. Finally, CEFA uses correction additives (e.g. gypsum) to correct the chemical composition of the clinker after switching from petroleum coke to

CW. Therefore, firms should consider the usability of discarded products and compare this to the substituted virgin counterpart.

Table 10
Parameters related to usability.

Supplier	Clinker productivity loss [Kg/ton of clinker]	Fossil/Biogenic CO_2 emissions [ton/ton of clinker]	Use of correction additives (e.g. gypsum, etc.) [Kg/ton of clinker]
A	84	1.13/0.7	35
B	54	1.55/1.15	35
C	155	0.65/0.75	35
D	109	2.7/0	35

In summary, (in)direct transport, the affected waste handling activity and the usability form three E-SSC which explain most of the environmental impact following the selection of CW suppliers. Yet, the three E-SSC should not be pursued independently. By selecting highly usable CW, one might select a supplier whose position in the MSW trade network leads to substantial indirect transport. Moreover, it may also reduce the supply to an environmentally preferred waste handling activity on the end-market. Likewise, focusing on reducing indirect transport may lower the usability of the CW and may affect environmentally preferred waste handling activities. Finally, a sole focus on indirect transport may have a negative impact as it may affect environmentally preferred waste handling activities or may result in sourcing CW with a low usability. Therefore, as depicted in Fig. 4, the three E-SSC should be considered together to account for the inter-dependencies.

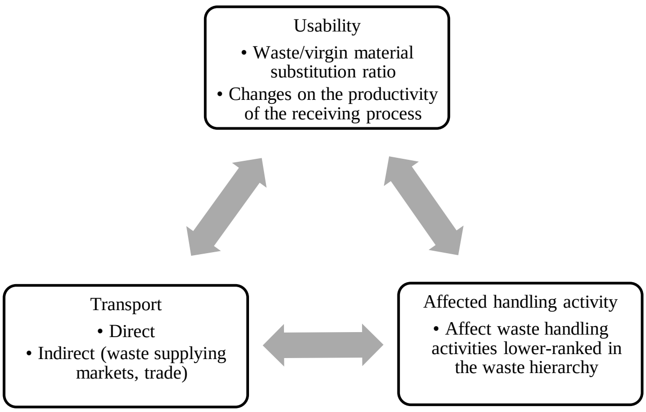

Fig. 4. Suggested E-SSC and inter-dependencies

A CLCA model helps to determine the respective contribution of transport, usability and the affected treatment option and indicates that, in the case of CEFA, efforts should be pursued to:

- maximize the avoided amount of waste disposed in landfills,
- while keeping the quality of the waste material as good as possible i.e. maximize the content of biogenic carbon and maintain a high net calorific value,
- and favor suppliers located on over-supplied end-markets to reduce indirect transport.

Nevertheless, when the resources to conduct a comprehensive CLCA lack, the proposed E-SSC provide guidelines for firms to select the most desirable supplier from an environmental stance.

5. Conclusion

Based on a CLCA, this study exposes three E-SSC which explain the environmental impact related to supplier selection in circular supply chains. The exposed E-SSC in the circular CW supply chain align with the predicted E-SSC in the literature review and build upon previous research. As theorized, the constrained supply of discarded products (Ekvall and Weidema, 2004) forms a key element behind the E-SSC for circular supply chains. Based on the constrained supply of discarded products, this research exemplifies that the environmental impact of (in)direct transport in forward supply chains – see e.g. Sim et al. (2007) – appears also relevant for supplier selection in circular supply chains. In line with Moberg et al. (2005), this research also highlights the impact of supplier selection on diverting discarded products from environmentally (ill-)favored waste handling activities due to the constrained supply. When also including the impacts of the usability of discarded products, the proposed set of E-SSC explain most of the environmental impact associated to supplier selection in the circular supply chain of CW. Therefore, by extending the findings of Moberg et al. (2005) and Ekvall and Weidema (2004) with the usability of discarded products and indirect transport, three generic and relevant E-SSC for circular supply chains are presented.

Due to the limitations inherent to a single case study, the significance of each E-SCC as well as the links between E-SSC provide potential avenues for future research. The findings should be considered in relation to cement production and need to be validated in other contexts. Being an energy-intensive industry, cement production gives a specific weighting on each E-SSC (e.g. the usability indicator has more weight on the end-results than transportation), which may be different than other sectors with other types of discarded products. Also, the amount of indirect transport likely depends on the maturity of the circular economy around a given discarded product. The use of discarded products which are abundantly available on an end-market does usually not trigger indirect transport as the overall availability decreases without limiting any of the demand-driven waste handling activities on that market. Future research should therefore test the importance of the proposed E-SSC and their interaction on large samples in other industries.

At the model level, the accuracy of the outcomes of the CLCA model are subject to three main sources of uncertainty. First, the amount of biogenic carbon per unit of CW is calculated based only on three carbon-dating tests per CW sample. This leaves room for error in the fossil carbon content as MRFs have often difficulties to keep the composition of CW stable over time. Inaccurate biogenic carbon estimates can potentially influence the emissions of greenhouse gas, which have a high monetization factor at the endpoint level. Second, the means and transport distances between CW markets are inaccurate. The preferred method, as illustrated by, amongst others, Jones (2002) and Caracciolo et al. (2017), uses exact distances – as done for direct transport in this study. When exact data is unavailable, estimates of minimum and maximum distances may prove sufficient (Jones, 2002). Unfortunately, estimating minimum and maximum distances for indirect transport between CW markets is deemed impossible due to several reasons. Potential trade within markets, the exact determination of the affected waste handling activity (e.g. which waste handling activity in the n^{th} market of the chain of trade is affected?), and the various transport routes between markets, complicates the estimation of minimum and maximum distances. Because of that, the use of the geographical centers of countries to estimate transport distances provides an objective and replicable method. A sensitivity analysis based on richer data is needed to determine the sensitivity of the end-results regarding inaccurate transport distances. In addition, based on interviews with MRFs, it is assumed that transport takes place by truck whenever possible, whereas CW can also be transported via inland waterways. Third, using a country resolution as a means for identifying waste markets has its limitations. Regions within large countries may have distinct MSW markets that would have different trade patterns. Since this study aims to develop E-SSC for circular supply chains and to demonstrate their need rather than to provide a detailed CLCA for CW combustion, the findings are not expected to be invalid due to the above described uncertainties. In the future, it is preferable to handle parameters and model uncertainty via uncertainty-handling techniques such as a Monte Carlo analysis to avoid biases towards a given supplier.

Consequently, this research is a first step that demonstrates the need to understand and consider the mechanisms behind E-SSC for circular supply chains. Moreover, this study contributes to practice by providing firms with guidelines for responding to environmental pressures and for achieving cleaner production within their circular supply chains.

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PAPER IV

Prosman, E.J. (2018), “A framework for environmental and economic supplier selection in industrial symbiosis. Insights from the cement industry”. *Working paper*

A framework for environmental and economic supplier selection in industrial symbiosis: insights from the cement industry

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Abstract
Although industrial symbiosis – the practice of re-using waste and byproducts from other industries – often offers environmental and economic benefits, firms may optimize the economic benefits at the expense of the environmental benefits. This paper investigates the trade-offs and synergies between environmental and economic benefits based on a case study in the cement industry. Three key findings suggest that cement producers 1) can optimize both environmental and economic performance by focusing on waste and byproduct quality 2) more surprisingly perhaps, can optimize their economic and environmental performance through focusing on the purchasing price of waste and byproducts as cheap waste and byproducts are often landfilled and not used by other industries and 3) might focus on minimizing the transport between them and the first-tier supplier to improve economic and environmental performance, while a high focus on this may erode net-environmental performance due to supply system wide impacts. The propositions and conclusions of this study are relevant for cement producers and similar industries who are engaged in industrial symbiosis and the circular economy as it provides insights into optimizing both economic and environmental performance. In addition, this paper gives insights to policy makers on how to align economic and environmental goals.

1. Introduction

The cement sector is under close scrutiny as the sector emits 5-7% of the world's greenhouse gas emissions, making cement the second largest industrial source of greenhouse gases (Allwood and Cullen, 2011). Moreover, due to explosive economic growth in the developing world, greenhouse gas emissions from the cement sector are projected to increase by 111% between 2005 and 2030 (Naucler and Enkvist, 2009). However, although (mostly experimental) technologies such as carbon capture and storage (CCS) became available, the sheer capital cost of the technologies to make cement making more environmentally benign prevents their adoption. Even incremental improvements such as adding preheater cyclone stages, improving the burnability of the raw-mix and pre-drying the (waste-based) fuel often requires investments of over 10 million euro per plant (ECRA, 2017). As such, other measures, which rely upon both economic and environmental performance, may be more beneficial and more realistic to achieve sustainable development in the cement sector in the near future.

The most commonly cited definition of sustainable development probably comes from the Brundtland Report, a report published by the World Commission on Environment and Development (1987, p. 41): "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Other seminal works added to our current understanding of sustainable development too. *The Limits to Growth* by Meadows et al. (1972) – a report on a computer simulation about economic growth and population growth constrained by a finite supply of resources – highlights the limited availability of the earth's resources as an important ingredient of sustainable development. Furthermore, John Elkington, in *Cannibals with Forks: the Triple Bottom Line of 21st Century Business* argued that one has to consider the trade-offs and synergies between what became known as the triple bottom line: economic performance, environmental performance and social performance (Elkington 1997). Sustainable development gained momentum in the last decades, as illustrated by the Millennium Goals and, later, the 17 sustainable development goals of the United Nations[14].

[14] The 17 sustainable development goals of the United Nations address issues such as, but not limited to, poverty, education, (gender) equality, clean energy, sustainable cities, pollution and climate change. The United Nations aim to accomplish the goals by 2030 (United Nations, 2015).

Although social performance is a major part of sustainable development, this research focuses on environmental and economic performance since, as evident from the first lines of this paper, those two spheres of sustainable development are of utmost importance for the cement industry.

To achieve sustainable development in terms of environmental and economic performance, the concept of a *circular economy* is gaining traction. This is evident through for instance the Circular Economy Production Law of the People's Republic of China (The Standing Committee of the National People's Congress China, 2008) and the European Circular Economy package (European Commission 2015). Industrial symbiosis – the practice of reducing the environmental impact through economically attractive waste and byproduct exchanges between firms (Chertow 2000) – plays a prime role in the circular economy by re-looping waste and byproducts back into the economy (Geng & Doberstein 2008; Ghisellini et al. 2015). In doing so, industrial symbiosis responds to the 12th sustainable development goal of 'responsible consumption and production'. Hence, industrial symbiosis provides a promising avenue for reducing the environmental impact of cement production in an economically attractive manner.

Yet, although the link between environmental and economic performance seems obvious in industrial symbiosis, exploiting both environmental and economic aspects may become challenging in practice due to factors related to supplier selection. Various supplier related aspects, such as waste and byproduct quality, can lead to both suboptimal economic performance (Prosman et al. 2017) and suboptimal environmental performance (Prosman & Sacchi 2018). However, how to select suppliers based on both economic and environmental performance in the context of industrial symbiosis is not yet well understood. In fact, existing multicriteria supplier selection models such as the Analytical Network Process (ANP), Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Data Envelopment Analysis (DEA) have not considered the context of industrial symbiosis (Prosman & Sacchi 2018). In fact, to the best of our knowledge, synergies and trade-offs between economic and environmental supplier selection criteria for industrial symbiosis are not yet identified in literature, even though such synergies and trade-offs have been extensively researched in many other contexts (Oliveira et al. 2018). This research therefore sets out to *identify synergies and trade-offs between environmental and economic supplier selection criteria in the context of industrial symbiosis in the cement industry*. We especially focus on the cement industry as 1) the cement industry is a key player in industrial symbiosis – see for example the case descriptions of Baas and Boons (2004), van Beers et al. (2007) and Mirata and Emtairah (2005) and 2) as evident from the first paragraph of the introduction, there is a clear need for environmental improvement in an economically viable way.

The propositions developed in this paper contribute to literature as, even though industrial symbiosis has enjoyed an immense interest from academia and the number of papers on how to organize industrial symbiosis has ballooned – see e.g. Srivastava (2007); Seuring and Müller (2008); Carter and Rogers (2008); Fahimnia et al. (2015); Govindan et al. (2014); Gimenez and Tachizawa (2012); Ilgin and Gupta (2010) – literature does not addresses the alignment of environmental and economic goals through supplier selection in the context of industrial symbiosis, let alone the context of cement production. The findings may also apply outside the cement industry as many industries have similar characteristics, such as the energy intensive process industry.

The remainder of this paper is organized as follows. First, the literature background elaborates on the economic and environmental impact of supplier selection in the context of industrial symbiosis. Next, the methodology is presented followed by the findings and the discussion where propositions are presented. Finally, a conclusion is made as well as directions for future research.

2. Literature background

Traditional thinking in industrial firms often holds that efforts to increase environmental performance should be at a minimum as going beyond this will unnecessarily increase costs (Sharma 2010; Evans 2017). Therefore, to explore the research aim to *identify synergies and trade-offs between environmental and economic supplier selection criteria in the context of industrial symbiosis in the cement industry*, it is important to first understand which factors affect the economic and environmental performance. The following paragraphs elaborate on this.

2.1. Environmental performance

Literature and the current perception (of politicians and firms) holds that the circular economy, including industrial symbiosis, has a positive environmental impact (Geissdoerfer et al. 2017). However, research also warns for negative environmental effects, such as not using the most environmentally benign material re-loop options. In fact, industries like the cement industry are often criticized for non-optimal environmental solutions for their industrial symbiotic activities (Moberg et al. 2005; Schmidt et al. 2007;

van Oss & Padovani 2003). To understand the environmental impact of industrial symbiosis, one has to consider the peculiar context of industrial symbiosis (Prosman & Sacchi 2018).

2.1.1. Context of industrial symbiosis and the effect on environmental sustainability
Forward supply chains differ from circular supply chains (Tibben-Lembke & Rogers 2002). In industrial symbiosis, the supply side of the market is dictated by the production of the goods from which the waste and byproducts derive, as such resulting in a bounded supply (de la Fuente et al. 2008; Ekvall & Weidema 2004). The amount of fly ash, for example, is bounded based on the amount of energy produced through coal combustion. An increase in demand for fly ash, except for some very extreme cases perhaps, does not lead to an increase of coal combustion. In forward supply chains, supply is less bounded: an increase for a given product or material can often be met by increased production, mining or harvesting (Naylor et al. 1999), even in the case of rare earth metals (Mudd et al. 2017).

Due to the bounded supply, environmental selection criteria should go beyond the supplier selection criteria often seen in literature such as green packaging, ISO 14001, eco-labelling, green process planning, up-to-date pollution permits, product-design for reuse, and waste water treatment – see e.g. Bai and Sarkis (2010), Freeman and Chen (2015), Govindan et al. (2013), Handfield et al. (2002), Lu et al. (2007) and Zhu and Sarkis (2004). Although such supplier selection criteria can also be relevant for industrial symbiosis, the bounded supply can have a major environmental impact on supply chains for industrial symbiosis. The following paragraphs present the, until now very scarce, literature on environmental supplier selection in the context bounded supply in industrial symbiosis.

First, transport related emissions within supply chains beyond the first-tier supplier can be significant compared to the transport between the buyer and the first-tier supplier (Sim et al. 2007). In fact, Liotta et al. (2015), Wang et al. (2011) and Sundarakani et al. (2010) show that changing the first-tier supplier can lead to an overall reduction of greenhouse gas emissions in the entire forward supply chain. Likewise, Prosman and Sacchi (2018) show that, in the context of industrial symbiosis, transport related emissions beyond the first-tier supplier can be significant due to the bounded supply of waste and byproducts. When a buyer sources waste and byproducts on a supply bounded market, the buyer can create a shortage of waste and byproducts on the market (Ekvall & Weidema 2004). Other firms located in this market may, in response to the shortage, import waste and byproducts from elsewhere. The import of waste and byproducts from elsewhere can create a shortage of waste and byproducts on other markets. This domino effect will continue until 1) firms decide to use other (virgin) materials instead of waste and byproducts or 2) when there is a sufficient supply of waste and byproducts to match the demand. In short, buying waste and byproducts may lead to additional transport due to other firms who start to import waste to overcome local shortages (Prosman and Sacchi 2018).

Second, resource efficiency is a key aspect to increase the environmental performance of our economy (Geissdoerfer et al. 2018; Stahel and Reday, 1976). Important herein is the restorative capacity of firms and supply chains where products, components and materials are kept at their highest utility and value (Webster, 2015). This can be achieved through maintenance, repair, reuse, remanufacturing, refurbishing and recycling (Geissdoerfer et al. 2017) (Ellen MacArthur 2013a, 2013b, 2013c). In the context of reuse through industrial symbiosis, this implies using waste and byproducts at their highest utility. However, using supply bounded waste and byproducts, avoids the use of the same waste and byproducts elsewhere – e.g. the fly-ash used by one factory cannot be used in another factory. In terms of environmental impact of waste and byproducts, *disposal* < *energy recovery* < *recycling* < *reuse* < *reduction* < *prevention* (Moberg et al. 2005; Schmidt et al. 2007). Therefore, to have a positive environmental impact, firms should not use the waste and byproducts from environmentally preferred waste treatment activities. The usage of waste and byproducts in the cement industry is relatively mature compared to other industries. For example, currently, there is a shortage of fly ash because of the extensive use in cement, concrete and road filling and the closure of several coal-fired power stations. Likewise, the availability of waste-based fuels is on the decline due to increased incineration capacity and increased recycling in many countries. As such, cement producers are likely to take away waste and byproducts from environmentally preferred waste treatment activities such as recycling, thereby possibly not creating any environmental benefits.

2.1.2. The impact of quality of waste and byproducts on environmental sustainability
The quality of the waste and byproducts also affects the environmental performance. Depending on the quality of the waste and byproducts, additional processing may be needed (Blackburn et al. 2004; Guide et al. 2000). The additional processing can increase environmental impacts (Chen et al. 2010; Fijał 2007). Moreover, using poor quality waste and byproducts in a capacity constrained process plant like a cement

plant, may result in lower production output (Prosman et al. 2017; King 2009). The opening of additional production lines (at the own plant or at other plants) may be needed to fulfill the final product demand, likely resulting in higher energy use and higher waste generation (Prosman & Sacchi 2018).

In sum, three factors determine the environmental performance of supplier selection in the context of industrial symbiosis:

- Transport of waste and byproducts.
  - Direct transport: between the buyer and the supplier
  - Indirect transport: beyond the first-tier supplier
- Avoided use elsewhere in the supply network.
- Quality of the waste and byproducts.

2.2. Economic performance

Economic performance remains still a prime concern of firms and often forms a barrier for adopting more environmentally benign practices (Oliveira et al. 2018; Ansari & Kant 2017). The economic performance of waste and byproduct exchanges, from the perspective of the buyer, is as practically every purchase influenced by the purchasing price and transportation costs (Ellram 1995). However, the economic performance of purchasing and supplier selection does not solely hinge on those two factors and requires a 'total cost of ownership' perspective (Ellram 1995). In fact, quality of supply can have a major impact on the economic performance of practices such as industrial symbiosis (Guide et al. 2000; Blackburn et al. 2004; Prosman et al. 2017). Waste and byproducts often have a lower quality and a higher variety in quality than the virgin materials they substitute (Bansal & Mcknight 2009). The lower quality can lead to production issues in terms of production capacity, final product quality, downtime in the factory (Prosman et al. 2017), thereby leading to uncaptured value (Yang et al. 2017) such as a lower turnover as a result of the reduced capacity and the lower quality. This is especially true in the cement industry, where quantities are high and where the 24/7 nature of the production process does not allow for compensating production losses by overtime and where the reprocessing of defect products (e.g. reprocessing low quality cement in the production system) is not possible (King 2009). The costs of low quality of waste and byproducts can therefore be significant, thereby justifying a total costs of ownership approach to assess the economic performance.

In sum, three factors determine the economic performance of selecting waste and byproduct suppliers:

- Cost of direct transport to transport the waste and byproducts to the production facility
- Purchase price of the waste and byproducts
- The quality of the waste and byproducts.

A fourth factor could be the environmental taxes. However, this factor has a very direct link with the environmental performance and does, therefore, not require further exploration in terms of the synergy between environmental and economic cost. Moreover, criticizing the environmental tax system goes beyond the scope of this paper.

2.3. Overview and research aim

The economic and environmental supplier selection criteria presented above are summarized in framework in figure 1.

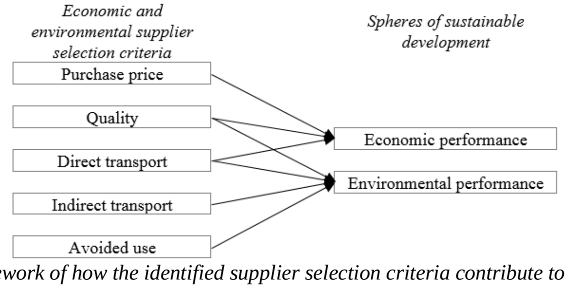

***Figure 1**. Framework of how the identified supplier selection criteria contribute to economic and/or environmental performance.*

As evident from figure 1, there are some seemingly obvious links between supplier selection criteria and economic and environmental performance (i.e. quality and direct transport affect both economic and environmental performance). However, also evident from figure 1, insights into trade-offs and synergies in terms of economic and environmental performance for the other economic and environmental supplier selection criteria in the context of industrial symbiosis in the cement industry lack. To economically improve the environmental performance of the cement industry, the next section presents the methodology to explore the research aim to *identify synergies and trade-offs between environmental and economic supplier selection criteria in the context of industrial symbiosis in the cement industry.*

3. Methodology

To empirically explore the link between economic and environmental performance in the context of industrial symbiosis in the cement industry, a consequential life cycle assessment (CLCA) was combined with a comprehensive total cost of ownership economic assessment based on a case study (Eisenhardt 1989). CLCA is a comprehensive tool to assess the environmental performance of supply chain operations (Matos and Hall 2007).

The case under investigation is the industrial symbiotic activities at "Cema" – a globally operating cement manufacturer who is heavily engaged in industrial symbiosis. The symbiotic activity under investigation is the alternative fuel, which is the combustible residue of processing municipal waste at material recovery facilities. For the economic assessment and the CLCA, four of Cema's alternative fuel suppliers are selected based on their different characteristics on (see figure 1):

- *Economic performance*
    - Different quality of the alternative fuel
    - Different purchase prices
    - Different locations (different direct transport)
- *Environmental performance*
    - Different quality of the alternative fuel
    - Different location
        - Different direct transport
        - A different location is an indicator of different avoided use and different (in)direct transport as they operate on different graphical markets with different waste processing and different availability of waste (Prosman & Sacchi 2018).

For the four suppliers, the economic performance is assessed based on a total cost of ownership approach whereby the unit of analysis is the costs for the buyer – in this case Cema. The environmental performance is assessed through a CLCA whereby the goal of the CLCA is the environmental impact of producing one ton of clinker (the main binding ingredient of cement) with the alternative fuel of the suppliers and the scope of the CLCA is a "cradle-to-production" – i.e. comprising all activities in the supply network and production environment. The next sections elaborate on data collection and the data analysis.

3.1. Data collection

Both economic data and environmental data were collected as input for the economic total cost of ownership assessment and the CLCA. Table 1 provides an overview of all the data sources and relates this to the purpose of this research. The combination of qualitative and quantitative sources for each of the supplier selection criteria resulted in data triangulation and increased the construct validity of the study (Voss et al. 2002; Yin 2013).

Table 1. *Overview of the collected data.*

Supplier selection criteria (between brackets the related sustainable development aspect)	*Data*	*Source(s)*	*Purpose*
Direct transport (economic)	Transport cost	Purchasing department + contracts + invoices	Input for calculating the transportation cost.
Purchase prices (economic)	Purchase price	Purchasing department + contracts + invoices	Input for calculating the purchase price.
Quality (both economic and environmental)	Alternative fuel analyses	Laboratory	Input for calculating the economic impact of alternative fuel quality on the production system. Input for calculating the environmental impact of the alternative fuel per supplier.
	Production data	Production system	Input for calculating the impact of the alternative fuel quality on the production process such as the production loss, running costs and breakdowns. Input for calculating the environmental emissions of the production stage for the different alternative fuel suppliers.
	Interview data	Interviews with production managers, operators and lab employees of Cema	Input for economic assessment and the CLCA. Explaining the data and validating the calculations.
Indirect transport and avoided use (both environmental)	Alternative fuel trade data	EuroStat (2013) data series	Input for modelling the alternative fuel supply network. The outcome serves as input for the CLCA.
	Interview data	Interviews with CEOs of the selected alternative fuel suppliers	Input for modelling the alternative fuel supply network. The outcome serves as input for the CLCA and validation of the CLCA.
Direct and indirect transport (both environmental)	Environmental impact data for transport	EcoInvent 3.2 database	Input for the transport related input for the CLCA.
Avoided use (environmental)	Alternative fuel generation data	EuroStat (2013) data series	Input for estimating the avoided use based on the methodology of Weidema et al. (1999). The outcome serves as input for the CLCA.

3.2. Data analysis

Based on the collected data, a two-step approach was followed. First, the economic and environmental costs were calculated. Second, the economic and environmental costs were analyzed together with supply chain, purchasing and environmental experts from Cema in order to identify synergies and trade-offs. The next paragraphs further elaborate on this.

3.1.1. Calculating the economic and environmental costs

First, the economic and environmental impact of the four suppliers was calculated. In terms of the economic costs, the collected data served as input to calculate the overall economic cost through:

- Modeling the kiln performance depending on the quality of the fuel, thereby calculating the economic cost of reduced production capacity, breakdowns and additional running cost due to alternative fuel quality of each of the suppliers.
- Calculating the purchasing cost of alternative fuel quality for each of the suppliers.
- Calculating the transportation cost of alternative fuel quality for each of the suppliers.

To ensure the reliability of the economic assessment, the economic data was analyzed and verified by plant managers, supply chain managers and purchasing managers of Cema. The collected data also allowed to perform a CLCA which included:

- The environmental costs of direct and indirect transport for each of the suppliers, following the methodology of Prosman and Sacchi (2018) and Sacchi (2017).
- The environmental costs of avoided use for each of the suppliers, following the methodology of Weidema et al. (1999).
- The environmental costs of the alternative fuel quality of each of the suppliers based on the impact on the production system.

The CLCA was conducted in conformance with ISO14040:2006 and ISO14044:2006. The environmental impact of the different suppliers was calculated by the impact characterization method StepWise2006 v1.5, which relies on established impact assessment models (IMPACT2002 + and EPID2003). Factors such as global warming, respiratory organics and inorganics, eco-toxicity, nature occupation, human toxicity, eutrophication, acidification, mineral extraction and ozone layer depletion were considered as these factors are found to have a major impact on industrial symbiosis (Schmidt et al. 2007; Prosman and Sacchi 2018). The environmental impacts were monetized using the following monetization factors presented in table 2 to allow for comparison with the economic costs. Both the economic and environmental costs were transformed using a key to ensure confidentiality of Cema's figures.

***Table 2**. Monetization factors used by StepWise2006*

Impact factor	*Unit*	*Monetization factor*
Nature occupation	Euro/m^2-year of agricultural land	0.124
Mineral extraction	Euro/extra MJ needed	0.0041
Human toxicity, non-carcinogens	Euro/kg C_2H_3Cl-eq	0.2712
Global warming, fossil	Euro/kg CO_2-eq	0.083
Respiratory inorganics	Euro/person*ppm*hour	67.602
Human toxicity, carcinogens	Euro/kg C_2H_3Cl-eq	0.264
Eco-toxicity, aquatic	Euro/kg TEG-eq	7.4E-6
Photochemical ozone, vegetation	Euro/m^2*ppm*hour	3.71E-4
Acidification	Euro/m^2 of unprotected ecosystems	0.0077
Ionizing radiation	Euro/Bq C-14-eq	2.0E-5
Eco-toxicity, terrestrial	Euro/kg TEG-eq	11.05E-3
Ozone layer depletion	Euro/kg CFC-11-eq	103.11
Eutrophication, aquatic	Euro/kg NO_3-eq	0.1014
Respiratory organics	Euro/kg PM 2.5-eq	0.26
Eutrophication, terrestrial	Euro/m2 of unprotected ecosystems	0.0124

3.1.2. Identifying synergies and trade-offs between economic and environmental supplier selection criteria
To identify synergies between the economic and environmental costs, the calculated costs were first analyzed and discussed together with supply chain, purchasing and environmental employees of Cema as well as the CEO, operations managers and sales manager of one of the alternative fuel suppliers. The discussions were iterative in nature. During the discussions, the involved employees commented on the identified synergies and trade-offs between the economic and environment supplier selection criteria – see table 3 for an overview of the involved employees of Cema and the supplier. Next, peer debriefing – i.e. engaging researchers which are not involved in the research – was used to discuss the identified synergies which were then finally presented to Cema again. Both the iterative rounds of discussions with Cema and the beer debriefing helped to finetune the findings and to increase the internal validity.

***Table 3**. Involvement of employees in identifying synergies and trade-offs between economic and environmental performance*

Employee's role in Cema	*Number of iterations*	*Employee's role at the supplier*	*Number of iterations*
Supply chain director	3	CEO	2
Category manager (alternative fuel)	3	Production manager A	3
Purchaser	1	Production manager B	1
Controller	1	Sales manager	2
Finance specialist	2	Finance specialist	1
Production manager A	2		
Production manager B	2		
Quality manager	2		
Environmental specialist	4		

4. Results and discussion

The following sections present the economic performance and the environmental performance of the four selected suppliers. Propositions, both novel and rather obvious ones which are already covered in literature, are presented to build a framework of links between economic and environmental supplier selection criteria at the end of this section.

4.1. Quality -- Purchase price

The economic costs are depicted in table 4. From the table, it is obvious that quality, direct transport and purchase price can play a large role in the economic performance of industrial symbiosis. However, whereas quality is a major cost for all four suppliers, direct transport and purchase price can be low due to, respectively, the proximity to the supplier and the applied gate fee. (The suppliers pay a gate fee to Cema instead of Cema paying them – an exception is supplier B who receives a small amount from Cema). The gate fee, to a certain extent, reflects the quality of the alternative fuel: the supplier with the highest quality cost pays the highest gate fee and the supplier with the lowest quality cost pays the lowest gate fee. However, due to inefficiencies in the contracts (due to negotiations, the mechanisms of supply and demand and power), the quality costs are not completely reflected in the purchase price / gate fee. Nevertheless, although obvious and although similar situations are already covered in literature (see for example Gray and Handley (2015)), our first proposition is:

> *P1. The quality of waste and byproducts is reflected in the purchase price in the context of industrial symbiosis in the cement industry.*

***Table 4**. The economic performance of the four alternative fuel suppliers. Negative purchase prices reflect a price paid to the buyer for taking the waste, i.e. the gate fee.*

Supplier	*Quality*	*Direct transport*	*Purchase price*	*Total economic costs*
A	€ 14.96	€ 9.50	- € 9.70	€ 18.23
B	€ 15.88	€ 4.00	€ 0.73	€ 17.61
C	€ 12.49	€ 25.25	- € 29.20	€ 15.54
D	€ 19.81	€ 6.80	- € 15.19	€ 7.42

4.2. Avoided use -- Indirect transport

The environmental performance of the four alternative fuel suppliers is given in table 5. One interesting observation is the low environmental cost of indirect transport and avoided use for supplier C. This is explained by the fact that the alternative fuel of supplier C would otherwise have been landfilled (positive environmental impact on avoided use) and, therefore, does not trigger any indirect transport (e.g. no incineration plants who have to import waste due to a shortage on the market). Based on this observation, the second proposition is:

> *P2. Low environmental costs for avoided use (avoided landfill) correlates with low environmental costs for indirect transport in the context of industrial symbiosis in the cement industry.*

***Table 5**. The environmental performance of the four alternative fuel suppliers. Negative costs for avoided use indicate that (some of) the alternative fuel was taken away from a lower ranked waste handling activity, hence resulting in a net-environmental gain*

Supplier	*Quality*	*Direct transport*	*Indirect transport*	*Avoided use*	*Total environmental cost*
A	€ 50.24	€ 0.98	€ 40.36	- € 45.95	€ 45.63
B	€ 58.19	€ 1.93	€ 24.92	- € 6.26	€ 78.79
C	€ 46.50	€ 5.67	€ 0.00	- € 47.01	€ 5.16
D	€ 72.68	€ 0.55	€ 22.01	- € 39.45	€ 55.79

4.3. Quality -- Economic and Environmental performance

When the economic cost for poor quality increases, the environmental costs for poor quality increases as well. In terms of economic costs, poor quality of alternative fuel led to production inefficiencies and a lower production output at Cema. Moreover, poor quality alternative fuel led to production stops. The 24/7 nature of Cema's production process did not allow for adding additional shifts to make up for the lost production. Therefore, the low alternative fuel quality directly translated into lost sales (since Cema can sell all the cement they produce). In addition, the poor quality of the alternative fuels increased the costs of sorting and handling the waste material on site as well as cleaning the production system after a production stop, thereby further increasing the economic costs of poor quality.

In terms of environmental costs, the low quality led to additional process emissions. The energy loss of the entire production system is almost stable and, therefore, the lower production output results in higher emissions per unit of output. However, the major share of the environmental costs due to poor alternative fuel quality came from replaced production: to fulfill demand, the reduced production capacity is fulfilled by opening additional production lines (elsewhere). Therefore, the third proposition is:

> *P3. The quality of waste and byproducts has a positive impact on the economic and environmental performance in the context of industrial symbiosis in the cement industry.*

This proposition is in line with the literature presented in section *2. Literature background* which showed that poor quality can increase both economic costs due to lost sales and additional processing (Guide et al. 2000; Blackburn et al. 2004; Prosman et al. 2017) and environmental costs due to reduced production capacity and inefficient processes (Prosman & Sacchi 2018; Chen et al. 2010; Fijał 2007).

4.4. Direct transport -- Economic and Environmental performance

The data suggests that direct transport affects both economic and environmental performance. Shorter transport distances translate in both economic and environmental savings. However, the economic costs of inter-modal logistics configuration (loading and unloading of both ships and trucks) and the different environmental and economic impact of different modes of transport (i.e. sea and road) also affect the relation between economic and environmental performance. Nevertheless, the fourth proposition is:

> *P4. Direct transport has a direct impact on both economic performance and environmental performance*

This proposition, including the effect of the mode of transport, is in line with the research presented by, amongst others, Caracciolo et al. (2017); Lin et al. (2014); Liotta et al. (2015).

However, as evident from table 5, the environmental cost of direct transport is relatively small compared to the other environmental costs. The relatively small environmental impact of direct transport at Cema can be explained by:

1. The high environmental impact of poor waste and byproduct quality on the energy intensive production process. This makes waste and byproduct quality a more important factor than direct transport.
2. The already extensive use of the waste and byproducts in the cement industry leads to high indirect transport. Waste and byproducts such as ashes, sludges and waste-based fuels already have a market and are, therefore, often taken away from other users who, in response, have to import waste from other markets. Therefore, indirect transport can have a large environmental impact compared to direct transport.
3. The environmental gains of going one step up in the waste pyramid (where disposal < energy recovery < recycling < reuse < reduction < prevention) often has a significant environmental

impact (Moberg et al. 2005; Schmidt et al. 2007) which outcompetes the environmental impact of direct transport.

Hence, although firms may have strong economic incentives to reduce direct transport, the environmental impact of such practices is relatively minor. Therefore, the next proposition is:

P5. The environmental cost of direct transport is relatively small in the context of industrial symbiosis in the cement industry.

The disbalance of economic and environmental costs for direct transport may lead to situations where cement producers optimize direct transport at the expense of the other factors with a larger environmental impact such as the avoided use and the quality of the waste materials. Hence, policy makers may therefore consider policy changes to align the economic and environmental sustainability.

4.5 Avoided use -- Purchase price

The purchase price correlates with the environmental costs of avoided use. The purchase price of waste and byproducts is lower when there is no other market, i.e. no competition for the waste and byproducts. Moreover, with the introduction of landfill taxes around Europe, the avoided economic cost of landfilling allows the suppliers to offer an appealing price for their waste and byproducts. At the same time, avoided landfilling also results in lower environmental costs (Moberg et al. 2005; Schmidt et al. 2007). The data in table 4 and 5 as well as the discussions with Cema's employees confirm this. Hence, the final proposition is:

P6. Avoided use affects purchase price in the context of industrial symbiosis in the cement industry

Figure 2 summarizes the propositions and combines them with the literature framework presented in *2. Literature background*. To clarify the novelty of this research, propositions which are in line with current literature are underlined, contrary to the newly presented propositions deriving from this research. Although some lines in figure 2 are not covered by the propositions, the empirical data in table 4 and table 5 is in conformance with the literature presented in *2. Literature background*. As such, presenting these links in figure 2 results in a more comprehensive framework.

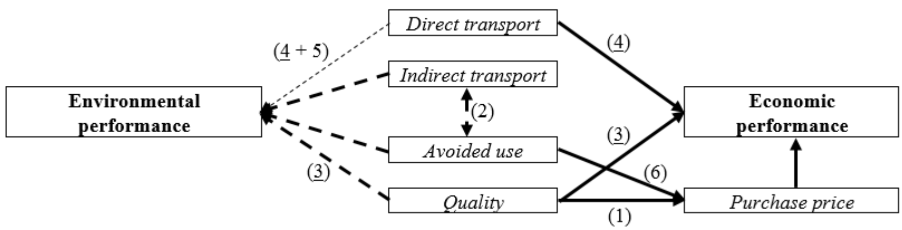

***Figure 2**. Framework of how the supplier selection criteria (in italic) contribute to economic and/or environmental performance. The dotted arrows refer to environmental performance; the solid arrows refer to economic performance. The thinner line represents a weak impact. The related propositions are between brackets where underlined propositions are already existing in literature.*

5. Conclusion

Based on a case study which explores the link between different supplier selection criteria and economic and environmental performance in the context of industrial symbiosis practices of cement production, several links between economic and environmental performance are identified and an overall framework is proposed. The developed propositions and framework add to the existing body of literature on economic and environmental supplier selection criteria because this is the first paper which provides an integrated perspective on environmental and economic supplier selection criteria in the context of industrial symbiosis. Hence, this study can help researches to understand the dynamics of supplier selection in the context of industrial symbiosis. Moreover, the propositions as well as the presented framework provide relevant research avenues. In addition, the proposed framework provides managerial insights by uncovering links between environmental and economic performance to managers involved in supplier selection in the context of industrial symbiosis. In addition, the findings have implications for policy makers as they indicate the danger of optimizing the direct transportation costs which might only lead to increment environmental gains related to direct transport and may potentially result in major environmental losses in terms of indirect transport, quality and avoided use.

Due to the limitations of a single case study, investigating the significance and validity of the findings provide an avenue for future research. Indeed, confirmatory work (e.g. survey studies) is needed to empirically test our propositions and to increase the validity and generalizability of the findings presented in this study. A particular weakness of the present study is the particular production set-up of Cema and the supply network of alternative fuel. This may render different results in other (cement) industries with different production set-ups or production set-ups tailored to the use of alternative fuel or firms who operate in less mature supply markets (with an abundant availability of waste and byproducts). Furthermore, the life cycle assessment would have benefited from richer data, which would allow for a sensitivity analysis for inaccurate transport distances, transport modes and alternative fuel quality in different geographic regions. Nevertheless, the presented findings provide useful insights for both academics and practitioners as it provides guidelines on how to achieve environmental and economic sustainability in the context of industrial symbiosis in the process industry.

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PAPER V

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Dare to make investments in industrial symbiosis? A conceptual framework and research agenda for developing trust

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Abstract

Scholars, policy-makers and industries increasingly express their interest in the development of industrial symbiosis (IS) to transition to cleaner production. Yet, many proposed IS instances never get implemented. In this article, we argue that a lack of clear understanding on how trust develops in the context of IS may prevent the implementation of new IS initiatives. New IS investments typically require upfront investments, such as pipelines, and take place in a cross-industry setting. This upfront and cross-industry setting of new IS investments may restrict firms in their ability to develop trust prior to the IS investments. Management literature provides a large body of literature on trust. Based on a multidisciplinary conceptual study, we synthesize and combine empirical and theoretical research from the fields of management and IS and theorize how trust applies to the field of IS, i.e. how firms can deploy certain strategies to develop trust prior to the IS investment in the context of upfront and cross-industry IS investments. As a result, this paper introduces a conceptual IS trust framework as well as an agenda for future research.

Keywords: trust, industrial symbiosis, investment, partnership, research agenda

1. Introduction

Industrial symbiosis (IS) aims to economically reduce the environmental impact of firms through the exchange and reuse of waste and byproducts (Chertow, 2000). IS contributes to higher resource efficiency and therefore forms a core part of the agenda towards more sustainable production practices. Trust between firms plays a vital role in establishing new IS relationships (Ashton and Bain, 2012; Ehrenfeld and Gertler, 1997; Sakr et al., 2011). Indeed, IS scholars argue that trust helps to reduce the risks related to the potential long-term commitment, long pay-back time and uncertain business conditions often seen in IS (Hiete et al., 2012). However, despite the acknowledged need of trust to establish IS relationships, how firms can develop trust in the context of IS is still not fully understood (Yap and Devlin, 2017). In fact, the context of IS differs from many other business relationships and may therefore alter the way in which trust develops.

IS relationships often take place *across different industries* and require *upfront* investments to enable the exchange and reuse of waste (Bansal and Mcknight, 2009). The *upfront* and *cross-industry* nature of IS investments may restrict firms in developing trust due to the lack of previous business transactions (Dwyer et al., 1987; Vanpoucke et al., 2014). Yet, the need for trust increases when the cross-industry nature leads to unfamiliarity with each other's business because the unfamiliarity may complicate the ability to judge the quality of the resources the other brings in or to audit the other's behaviour and performance (Brinkhoff et al., 2015; Kwon and Suh, 2005; Kwon and Suh, 2004). In fact, even an anticipated, high economic return from an IS exchange does not necessarily lead to investing in IS (Paquin et al., 2014). As such, the upfront and cross-industry nature creates a context in which trust plays a peculiar and not yet fully understood role. Knowledge of what fosters the required trust levels for upfront and cross-industry IS investments remains rather undeveloped (Paquin and Howard-Grenville, 2012) and benefits from further research (Velenturf and Jensen, 2016). Management literature offers ample insights into how trust between firms develops and how and why trust may play a pivotal role in potential IS investments.

This article merges literature in the fields of IS and management to explore the role and development of trust in setting up IS relationships. Insights from management literature are applied and discussed in the context of upfront and cross-industry IS investments. In doing so, we explore the following research question: *how can firms develop trust prior to upfront and cross-industry IS investments*? Based on this exploration, we develop a conceptual framework and research agenda for developing trust in the context of IS.

The conceptual framework and research agenda contribute to literature and practice. Currently, the state-of-the-art literature on trust in IS lacks a framework and a research agenda on how to advance knowledge about trust development in IS. For example, literature searches in Scopus, Web of Science and ScienceDirect revealed no proper research agendas on the topic of trust and IS and no research which combines management literature with IS literature to develop knowledge on trust emerged. As Pagell and Shevchenko (2014) argue that the integration of multidisciplinary fields is required to advance the field of sustainability, this research contributes to literature by 1) demonstrating how management literature and IS literature are related in terms of trust and 2) by proposing a conceptual framework and research agenda for future research. Moreover, the developed framework may help firms, governments and third-party facilitators to establish the needed trust for upfront and cross-industry IS investments thereby helping firms to transition towards cleaner production.

We structure the paper as follows. The next section sets the stage by shortly introducing the concept of IS and elaborating on the need for trust in upfront IS investments. Section 3 presents the research procedure and the methods applied in this study. Section 4 includes the present limited perspective on trust in the IS literature, provides a detailed definition of trust and how trust develops in the context of IS. Furthermore, this section presents the existing strategies for developing trust according to management literature and discusses approaches for developing different levels of trust in the context of upfront and cross-industry IS investments. The conceptual framework on developing trust in IS is introduced in section 5. Section 6 provides a discussion and suggestions of how our work can serve as an avenue for future research. We conclude with section 7.

2. Background

2.1. Introduction to IS

IS is a concept deriving from the field of industrial ecology, related with the flow of resources on an inter-firm level (Chertow and Ehrenfeld, 2012). The usual resources exchanged between firms are wastes, materials, by-products, energy, water, and even know-how (Chertow, 2004). Scholars have studied the emergence of IS since the early 1900s (Yap and Devlin, 2017; Desrochers and Leppala, 2010). Kalundborg in Denmark is perhaps the most cited and well-known case of successful IS (Ashton, 2008; Ehrenfeld and Gertler, 1997). Other well-known instances of IS include Kwinana, Australia (van Beers et al., 2007), Rotterdam, The Netherlands (Baas and Boons, 2004), Styria, Austria (Schwarz and Steininger, 1997), the Guitang Group symbiosis in China (Zhu et al., 2007) and various cases across the United States (Heeres et al., 2004). IS may develop in a variety of ways, ranging from firms which self-organize the IS exchange (Chertow, 2007; Ehrenfeld and Gertler 1997) to central bodies such as governments, which plan IS using a top-down approach (Chertow, 2007; Gibbs and Deutz, 2007). In the middle of this spectrum, third-parties may facilitate certain aspects of the IS exchange such as bringing firms together: the so-called facilitated IS (Paquin and Howard-Grenville, 2012). In our research, we focus on self-organized and facilitated IS as firms themselves decide whether to partake and invest in IS rather than being forced to by governments in planned IS. IS developed through social networks are considered more adaptive systems (Chertow and Ehrenfeld, 2012), while governments imposing IS investments on firms may cancel out the need for trust between the firms (Velenturf and Jensen, 2016).

The unit of analysis of this research is the investing party's trust in the initial IS investment. The next sub-section elaborates on the required trust of the investing party.

2.2 The need for trust in the IS investment from the perspective of the investing party

Vanpoucke et al. (2014) found that investments in buyer-supplier relationships require high levels of trust of the investing party. Likewise, Ehrenfeld and Gertler (1997), Hiete et al. (2012), Velenturf (2015) and Panyathanakun et al. (2013) among others, observe a high need for trust in setting up and investing in IS relationships. The perceived risk of the IS investment affects the required level of trust of the investing party. When the investing party perceives the overall risk of the IS investment as low, lower levels of trust may suffice. On the contrary, the investing party may require higher levels of trust before making riskier upfront IS investments (Nooteboom et al., 1997). In the context of IS, the required level of trust might be high because risks for the investing party may arise from the following sources:

1. **Long payback time.** Although literature shows that implemented IS investments can have short payback times – see for example Park and Park (2014) who describe the short payback times for various investments in IS exchanges in South Korea and Jacobsen (2006) who describes short payback times of IS investments in Kalundborg – IS investments are often characterized by high

payback times (Hiete et al., 2012). The longer the payback time, the higher the risk that the investment does not pay itself back.

2. **Economic lock-in.** The economic lock-in effect refers to the risk of being solely dependent on a single supplier and looking for alternatives is expensive due to the asset specificity and high transaction costs typical in the context of IS (Zhu and Ruth, 2013). Case descriptions of amongst others Ashton (2008), Ehrenfeld and Gertler (1997), van Beers et al. (2007) and Baas and Boons (2004) show that most IS exchanges depend on only one supplier and that the asset specificity and transaction costs of the investment are high. Hence, in IS, there is often a high risk of "lock-in", which makes the investment dependable on the supplier.
3. **Incomplete and complex contracts.** IS investments are often accompanied by long-term and complex contracts (Jacobsen, 2006) which enable the IS exchange (Albino et al., 2015). However, firms cannot predict every potential risk because of their bounded rationality. Factors such as changing governmental regulations regarding waste handling can undermine the validity of the contract (Yap and Devlin, 2017). Furthermore, the complex context of IS, the size of the IS investment and the spontaneous and emerging adaptations of IS make it likely to overlook potential risks in the contract (Carpenter et al., 2009).

In addition, when the investing party is the buyer of the waste and byproducts, the required trust levels might be even higher because of the following reasons:

4. **Poor expected supplier performance.** Managing waste and byproducts is often not a core competence and core priority of IS partners (Bansal and Mcknight, 2009; Walker and Jones, 2012). The ability and willingness of the supplier to deliver in accordance with (strict) quality parameters might therefore be uncertain. Furthermore, suppliers might also underperform on other aspects such as on-time delivery in full and guaranteeing sufficient quantities of waste and byproducts in the future (Walker and Jones, 2012).
5. **Inflexibility of the receiving process.** The perceived risk of short falling supplier performance is lower when firms can counteract poor supplier performance. For example, by having a certain degree of flexibility in their own processes in terms of accepting waste and byproducts of varying quality. However, processes become increasingly optimized and become therefore less flexible towards varying waste and byproduct quality. This is especially true in the process industry (King, 2009), which is a major player in IS.

Long payback times, economic lock-in, incomplete contracts, poor expected supplier performance and inflexible receiving processes increase the perceived risk of the upfront investment. It is therefore not surprising that many IS scholars suggests that trust plays a vital role in establishing new IS relationships (Ashton and Bain, 2012; Chertow, 2007; Ehrenfeld and Gertler, 1997; Hewes and Lyons, 2008; Sterr and Ott, 2004; Yap and Devlin, 2017).

Literature provides some examples on how trust in IS can be developed – e.g. informal meetings at business clubs or at the golf court, making participants partake in participatory modelling and relying on third-party facilitators (Ashton, 2008; Batten, 2009; Hewes and Lyons, 2008; Jacobsen, 2006). Despite that, Paquin and Howard-Grenville (2012) argue that there is a lack of knowledge of what fosters trust. Fortunately, there are trust-creating strategies mentioned in management literature that have not yet been considered in the context of IS. To merge management and IS literature in a systematic way, the next section elaborates on the methodological research procedure.

3. Research procedure

This study is a conceptual study, which integrates two research fields: management literature and IS literature. A multidisciplinary conceptual study is a relevant method when research fields do not oppose each other and have not been linked to each other yet.

The above is the case for this study. Management literature offers a large body of literature on how trust between firms develops. However, although IS literature argues that trust is important (Ashton and Bain, 2012; Ehrenfeld and Gertler, 1997; Velenturf, 2015), research on trust in IS literature is in its infancy, especially when compared to management literature. A multidisciplinary conceptual study based on the integration of management and IS literature regarding trust is therefore an appropriate method to answer our research question: *how can firms develop trust prior to upfront and cross-industry IS investments*? The conceptual/theoretical approach for answering the research question is further justified by the absence of similar studies. An extensive search on Scopus, Web of Science and ScienceDirect considering titles, keywords and abstracts with the search strings "*trust*" combined with "*industrial symbiosis*" or "*industrial ecology*" and no restrictions to the fields of knowledge, did not lead to studies which clearly combined management and IS literature to develop knowledge about trust in the context of IS – even though several articles on the topic called for a deeper perspective on trust (Yap and Devlin, 2017). In addition, frameworks and conceptual studies are considered important for advancing the knowledge on topics related to sustainability and IS and are well-received in the scientific community (Angell and Klassen, 1999; Boons et al., 2011; Despeisse et al., 2012; Seuring and Müller, 2008) and conceptual studies which combine management literature and IS literature emerged in journals, such as the Journal of Cleaner Production - e.g. Herczeg et al. (2018). Our approach of integrating the two research fields follows the same procedure as Jabbour and De Sousa Jabbour (2016). The research procedure is provided in Figure. 1.

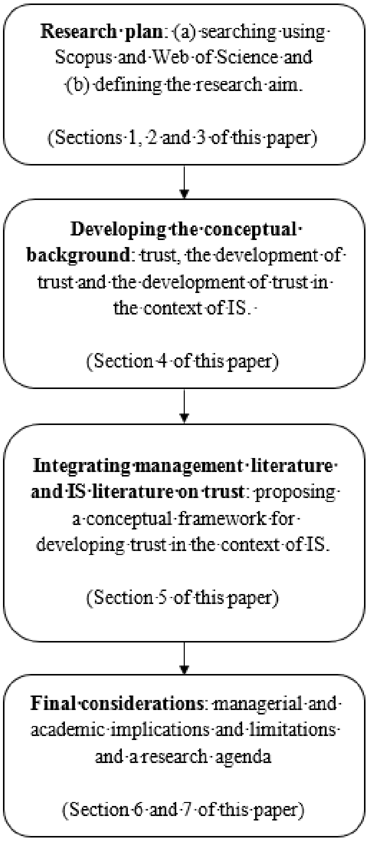

Figure 1. *Step-by-step description of the research procedure of this study. Based on Jabbour and De Sousa Jabbour (2016).*

4. Underlying theory

This section starts with arguing that current literature on IS adopts a limited perspective on trust. From there on, we define trust and we introduce strategies for the development of trust.

4.1. The limited perspective on trust in IS literature

Management literature and IS literature often hold a limited perspective on trust. In management literature, the mainstream view holds that trust emerges naturally as a result of exchanges (Dwyer et al., 1987; Gulati, 1995; Li et al., 2008) – e.g. relationship length is often used as a proxy for trust in survey studies. In the field of IS, trust is often described in general terms and lacks a sound analysis (Hiete et al., 2012). For example, Ehrenfeld and Gertler, (1997) refer to the role of trust in establishing IS as "*an atmosphere of trust in Kalundborg existed even in the absence of specific experience between firms*" (p. 74); Gibbs (2003) argues that "*many of the key barriers to EIP [eco-industrial park] formation revolve around issues of inter-firm networking, trust and the potential to cooperate*" (p. 230) and Ashton (2008) notes that: "*as a proxy for trust, respondents were asked to indicate which of the other managers [in the IS of Barceloneta, Puerto Rico] they would be willing to do business with personally, regardless of industry affiliation*" (p. 45). Hiete et al. (2012) takes a somewhat more elaborate perspective on trust by mentioning that in the initial stages of IS, IS partners rely on calculus-based trust. However, they do so without arguing why calculus-based trust is important and how calculus-based trust can be developed. Due to the limited perspective on trust in IS literature, how and why trust arises and enables upfront investments in the cross-industry context of IS remains unclear. In the remainder of this section, we first elaborate on the definition of trust before we introduce already existing strategies to develop trust based on management literature.

4.2. Definition of trust

Mayer et al.'s (1995) frequently cited definition of trust offers a useful avenue to explore how firms can develop trust in upfront IS investments. Mayer et al. (1995) refers to trust as "*the willingness of a party to be vulnerable to the actions of another party based on the expectation that the other will perform a particular action, irrespective of the ability to monitor or control that other party*" (p. 712). This definition carries notions of the belief in the other's ability, integrity and benevolence. These notions are similar to Sako's (1992) and Nooteboom's (2002) categorizations of competence, contractual and goodwill trust. Competence trust (ability) describes the belief that the other is capable enough to perform a given set of tasks; contractual trust (integrity) refers to the belief that the other will adhere to the agreements and accepted ethical principles; goodwill trust (benevolence) labels the confidence that the other will not show self-interested behaviour when an opportunity occurs (Crane, 2018; Sako, 1992).

Like all business relationships, the three notions of trust also apply in the context of IS investments. For example, the supplier might misrepresent their ability to control the overall quality or the quality variances in order to get rid of their waste and byproducts and avoid landfill taxes (Mirata, 2004; Park et al., 2008). Furthermore, IS partners might not act integer or benevolent for various reasons in the context of IS (Mirata, 2004; Park et al., 2008). Low levels of trust in the ability, integrity or benevolence of the business partner might ultimately put the upfront IS investment at stake.

4.3. The development of trust

Management literature argues that the development of trust moves through three different, yet complementary, trust bases (Shapiro et al., 1992; Lewicki and Bunker, 1995; Lewicki et al., 2006). The first trust base – calculus-based trust (CBT) – ensues from an economic estimation of the costs and benefits of the business partner for overstating their ability, (not) adhering to the agreements or (not) acting opportunistically in ambiguous situations. Based on this economic estimation, firms can estimate the likelihood that the other will act (un)trustworthy (Lewicki and Bunker, 1995; Lewicki et al., 2006). When business partners get to know each other better, trust development moves from CBT to knowledge-based trust (KBT). KBT relies on the ability to understand and predict the other's behaviour through knowledge, hence forming another basis of (dis)trust (Shapiro et al., 1992; Lewicki et al., 2006). Finally, when business partners start to identify themselves with each other and internalize each other's preferences, identification-based trust (IBT) develops (Lewicki et al., 2006). IBT relies upon the knowledge that the other is motivated to pursue joint outcomes rather than maximizing its own self-interest (Lewicki and Bunker, 1995). IBT only develops in a small subset of business relations. Developing the next trust base can already start in the preceding trust base. KBT can already develop from the beginning and IBT can develop even though KBT hasn't reached its peak yet (Lewicki and Bunker, 1995; Lewicki et al., 2006). In addition, it is possible to have different levels of trust for the different notions of trust (Lewicki and Bunker, 1995).

Shifting to the next trust base typically happens at specific points in the relationship, with trust levels quickly increasing in short time spans. This sudden shift in trust levels is explained by the increased intensity of the business relationship at a given point in time (Lewicki et al., 2006).

4.3.1. The development of trust in the context of IS

Increasing the intensity of the business relationship, as suggested by Lewicki et al. (2006) is often not possible in the context of IS. As demonstrated in case descriptions of amongst others Baas and Boons (2004), Ehrenfeld and Gertler (1997), Schwarz and Steininger (1997), van Beers et al. (2007) and Zhu et al. (2007), IS often requires *upfront* investments to process and transport waste and byproducts and to prepare waste and byproducts to meet exacting quality standards. See for example case descriptions of the Kalundborg symbiosis (Jacobsen, 2006) and the Guitang Group symbiosis (Zhu et al., 2007), which mention upfront investments such as pipelines and waste treatment equipment. Furthermore, from the aforementioned case descriptions it is evident that IS often take place in a *cross-industry* environment (Bansal and Mcknight, 2009). Literature describes various waste and byproduct exchanges such as fly ash, waste water, steam, sulphur and various minerals and chemicals between otherwise unrelated industries such as cement production, energy generation, oil and sugar refinery and more (Bansal and Mcknight, 2009; Chertow, 2007). The cross-industry nature further complicates increasing the intensity of the business relationship.

Figure. 2 graphically depicts the need for trust (section 2) and the research context, thereby showing that the strategies to develop trust should take into account the context of upfront investments and the cross-industry nature of IS.

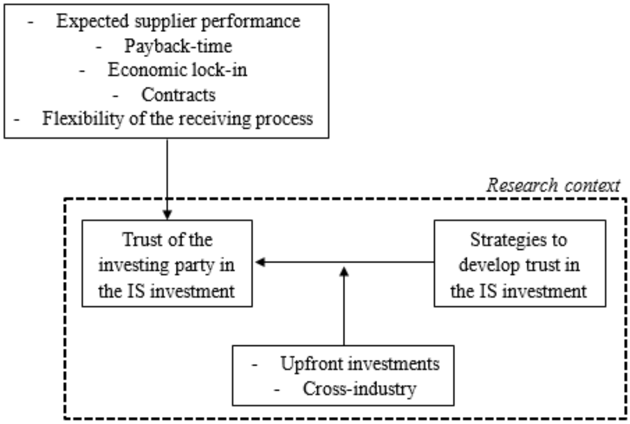

Figure 2. *The need for trust in IS investments and the research context of trust developing strategies (dotted box).*

4.4. Strategies for developing trust

Based on management literature, Ireland and Webb (2007) identify four strategies that firms can use to create trust between business partners (without specifying which notion of trust and which trust base), namely:

- boundary spanners
- common identity
- authority
- justice

We exclude the latter two strategies – authority and justice – from our further analysis. Authority enables the exertion of power and provides a source legitimate influence over the other firm while sustaining the current trust levels and is, therefore, not directly linked to creating trust. Justice requires previous business transactions to build up norms of reciprocity and is therefore out of the scope of this study due to the context of upfront investments (Ireland and Webb, 2007). Boundary spanners and common identity, on the other hand, can be applied in virtually every buyer-supplier relationship and firms can proactively apply these strategies to create trust without the need for business transactions prior to the IS investment. In fact, the strategies of boundary spanners and common identity also occur in IS literature.

4.4.1. Boundary spanners

The strategy of boundary spanners refers to gathering and sharing information about a firms' strategic intentions. As such, boundary spanners can provide transparency of the objectives and capabilities of potential IS partners (Ireland and Webb, 2007; Perrone et al., 2003; Zaheer et al., 1998). According to IS literature, boundary spanning agents (e.g. board-of-director interlocks, purchasing agents and IS champions) and third-party facilitators (e.g. Kalundborg Symbiosis Centre and the National Industrial Symbiosis Programme (NISP) can utilize their boundary spanning role to create trust. Hewes and Lyons

(2008), for example, show that so-called ‘champions’ play an important role in establishing trust. Champions are advocates of the IS exchange and can be persons from inside or outside the firm. However, at which stage of the trust creating process champions are useful for the investing party remains unclear. Moreover, whether or not their role changes throughout the trust creating process or whether or not different champions are needed remains unclear too. Likewise, although Paquin and Howard-Grenville (2009) claim that boundary spanners such as third-party facilitators (e.g. Kalundborg Symbiosis Centre and the NISP) can create trust, when and how the investing party benefits from third-party facilitators remains unclear. In addition, although mentioned as enablers for IS, the role of other boundary spanners such as public knowledge (e.g., company websites, certifications, reputation, etc.) and a shared network (e.g. common relationships) in terms of creating trust is not yet discussed in literature. Hence questions such as how and when to apply boundary spanners benefit from further exploration.

4.4.2. Common identity

The strategy of a common identity refers to establishing shared goals and norms that in turn become antecedents for developing trust within a relationship (Mayer et al., 1995). According to management literature, when firms identify themselves with a certain group, they act in a way that benefits those within that group (Ireland and Webb, 2007). A common identity can derive from cultural and geographical proximity (Lewicki et al., 2006). In the context of IS, a common identity often arrives from a shared ‘green profile’ and social proximity (often enabled through geographical proximity) (Paquin and Howard-Grenville, 2012; Sterr and Ott, 2004; Uzzi, 1997; Zhu, et al., 2015). However, developing a common identity may require significant time and the upfront nature of initial IS investments might not allow for this time. Nevertheless, when a common identity is already existing, the investing firm can capitalize on this. The question therefore is how and when to capitalize on a common identity in the context of IS.

5. Conceptual framework for developing trust in the context of IS

In the next paragraphs, we explore how the investing party can deploy the strategies of boundary spanners and common identity to increase the level of trust by progressing to the next trust base: from CBT to KBT and, eventually, to IBT. In this trust progression, we consider the context of upfront and cross-industry investment as well as the three notions of trust, i.e. ability, integrity and benevolence. We summarize our discussion in the conceptual framework presented at the end of this section.

5.1. Establishing calculus-based trust (CBT)

As already mentioned, CBT ensues from an economic estimation of the costs and benefits of the IS partner for overstating their ability and (not) adhering to the agreements or (not) acting opportunistically in ambiguous situations (Lewicki and Bunker, 1995; Lewicki et al., 2006). Therefore, strategies to develop CBT should gain insights into the costs and benefits of the business partner.

Boundary spanners can contribute to the development of CBT. Boundary spanning agents, such as purchase and operations managers, finance experts and lawyers, may arrange meetings with the potential IS partner to derive impressions and clues on which to base their estimation of the costs and benefits of the other for overstating their ability and not acting integer (Ireland and Webb, 2007). Likewise, boundary spanning agents can collect insights into the cost for the other when acting opportunistically. High costs for acting opportunistically reduces the likelihood for opportunistic behaviour, thereby increasing the CBT in benevolence. Furthermore, Paquin and Howard-Grenville (2009) claim that boundary spanners such as third-party facilitators (e.g. Kalundborg Symbiosis Centre) and a shared network can provide impressions and clues about the costs and benefits for the other based on their earlier experiences with the potential IS partner, thereby increasing the CBT in the ability, integrity and benevolence. Finally, publicly available knowledge, about disposal costs for example, may also contribute to the economic estimations.

A common identity, such as a shared ‘green’ profile or social proximity is unlikely to be a source of initial impressions and clues about the costs and benefits of the other for overstating their ability, not acting integer or not acting in a benevolent way (Lewicki et al., 2006).

5.2. Progressing to knowledge-based trust (KBT)

As discussed earlier, KBT relies on the ability to understand and predict the other’s behaviour through knowledge, hence forming another base of (dis)trust atop of CBT (Shapiro et al., 1992; Lewicki et al., 2006). The strategy of boundary spanners and common identity may be useful for gathering knowledge, thereby creating KBT.

Boundary spanning agents, such as purchase and operations managers, may arrange meetings with potential IS partners to better understand and predict the other’s behaviour (Ireland and Webb, 2007).

Quality checks of the material and process checks at the other's facilities can lead to insights into the other's ability. Furthermore, boundary spanning agents, such as purchasing and operations managers and board-of-director interlocks, can build up relationships with the other company prior to the investment. The relationships enable open communication and knowledge sharing and potentially lead to insights into the other's integrity and benevolence (Ireland and Webb, 2007). Furthermore, third-party facilitators such as the Kalundborg Symbiosis Centre may contribute to the development of KBT. Paquin and Howard-Grenville (2012), for example, show that the NISP in the United Kingdom gains insights into the ability of potential IS partners prior to the initial IS investment. These insights are then shared between the involved IS partners. In addition, third-party facilitators like Kalundborg Symbiosis Centre and the NISP can introduce firms to each other. As such, third party facilitators enable firms to use their own boundary spanning agents to gather knowledge about the potential IS partner (Paquin and Howard-Grenville, 2009). In addition, public knowledge (e.g. reputation and clearly stated business ambitions) exhibits capabilities and goals of the other party and can therefore create KBT in the ability, integrity and benevolence (Ireland and Webb, 2007).

The strategy of a common identity may contribute to KBT in terms of predicting the integrity and benevolence: when goals, norms and values are similar, the other is more likely to act integer and show benevolence.

5.3. Progressing to identification-based trust (IBT)

As noted, IBT develops when IS partners internalize each other's desires and intentions which leads to higher trust in the other's integrity and benevolence (Lewicki and Bunker, 1995; Lewicki et al., 2006). To develop IBT, boundary spanners and a common identity should lead to shared desires and intentions.

Boundary spanning agents can play a role in developing IBT by integrating firms on a strategic level and identify and establish shared goals, and as such create trust in the other's integrity and benevolence (Ireland and Webb, 2007). Due to the strategic nature, this probably requires the involvement and support of top-management and board-of-directors who should act as champions. However, time limitations may limit the role of boundary spanning agents as developing a common identity may be time consuming.

An existing common identity makes it unlikely that the other firm does not to adhere to agreements because it is against their own goals. Moreover, a common identity explicitly defines what is valued in reciprocity and the outcome of a reciprocal exchange that is being sought – i.e. if a firm is facing an issue, partners will aim to join forces in overcoming it (Ireland and Webb, 2007). So, a common identity can contribute to the development of IBT in terms of integrity and benevolence. Moreover, when firms identify themselves with a common identity in terms of industrial symbiosis, this common identity gives insights into the other's priorities. When IS receives high priority by the other firm, the other firm is more likely to develop the necessary IS capabilities, thereby increasing their ability. Hence, a common identity can provide trust in the other's ability.

The conceptual framework, depicted in Figure 3, illustrates the discussed strategies for the respective trust base and the associated notion of trust. The selected strategies are all applicable in the context of cross-industry upfront investments.

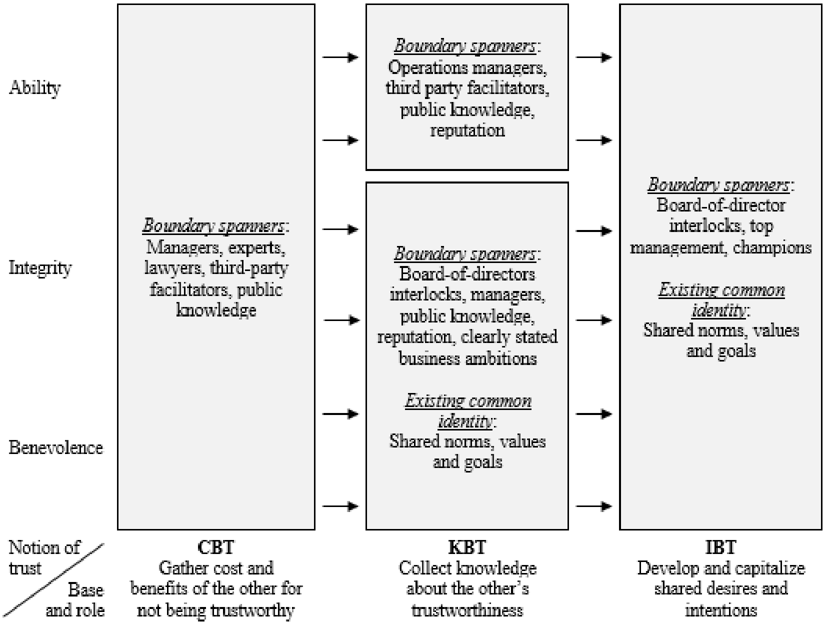

***Figure 3**. Conceptual framework for developing trust in the context of IS: strategies for progressing from CBT to KBT to IBT.*

6. Discussion and agenda for future research

The objective of this research is to answer our research question: *how can firms develop trust prior to upfront and cross-industry IS investments?* Based on literature from the fields of management and IS, a conceptual framework for developing trust in the context of IS is developed and presented. The conceptual framework describes which strategies firms can apply to increase trust and at which stage the strategies should be applied. Despite introducing new aspects of the way in which trust is developed, we acknowledge the need for further research on the topic. Therefore, we propose the following agenda for future research to further develop and operationalize the model:

1. *How much trust is needed for upfront and cross-industry IS investments?*
    a. *For which notion of trust?*
2. *How can firms accelerate the trust developing process?*
    a. *For each notion of trust*
    b. *For each base of trust*
3. *How effective is each strategy in developing trust and what are the barriers?*
    a. *For each notion of trust*
    b. *For each base of trust*
4. *Which contingency factors need to be considered and how, when and why do they affect the trust development?*
    a. *E.g. How and to what extend does the openness of the firms impact the development of trust in the context of IS?*
    b. *E.g. How and to what extend does geographic proximity impact the development of trust in the context of IS?*
    c. *E.g. Required level of trust*
    d. *E.g. How does power impact the effectiveness of creating trust through the strategies of boundary spanners and a common identity?*

Lewicki (2006) illustrates the relevance of the second question by means of an example. Saying hello to the child-care attendant every morning might eventually lead to getting to know this person. However, being stuck with someone in an elevator for two hours accelerates this process and might lead to high levels of knowledge and trust in the other only after two hours. In the context of up-front investments, accelerating the trust developing process can be essential for the implementation of the IS investment.

In relation to question 4a and 4b, Mirata (2004) reports that the openness of the firms involved in the IS affects the degree in which they trust each other. Whereas the petro-chemical firms and chemical firms in the Humber region in the United Kingdom did not trust each other due to a closed attitude towards other businesses, firms in the West Midlands trusted each other more easily due to a history of communication. Boundary spanning agents such as purchasers and board-of-director interlocks might thus be obstructed by a history of limited communication. Geographical proximity – although recently mostly hailed for technically allowing the exchanges of quickly degrading waste and byproducts or to economically enable the IS exchange (Lombardi and Laybourn, 2012; Shi et al., 2010) – can also ease the job of the boundary spanning agents as they can more easily meet in person. Moreover, geographical proximity makes it more likely that a common identity is already existing prior to the IS investment. However, the importance of geographic proximity remains rather unclear.

7. Conclusion

This research aims to explore and theorize about the development and role of trust in the context of upfront and cross-industry IS investments. In line with this, we analysed the following question: *how can firms develop trust prior to upfront and cross-industry IS investments?* The novelty of this study lies in providing an improved understanding of the development and role of trust in upfront cross-industry IS investments based on insights from the fields of management and IS. In doing so, this research contributes by providing:

1. An improved understanding on when to apply different trust developing strategies
2. An improved understanding on how to apply different trust developing strategies
    a. The role of boundary spanning agents, such as IS champions, changes when moving from CBT to KBT to IBT. In fact, an IS champion could be a different person depending on the stage of the trust development process
3. A conceptual framework and agenda for future research for developing trust

To validate the conceptual framework for developing trust in the context of IS we recognize the need for future research to address the shortcomings of our study. First, future research should use empirical data, either surveys or case studies, to test the usefulness of each strategy for developing a certain trust level (i.e. CBT, KBT or IBT) as well as the link to the notion of trust (i.e. ability, integrity or benevolence). Second, factors such as company size, industry, type of exchange, the uncertainty in the supplier's ability, size of the investment, competitive relationship between firms (albeit IS is typically cross-industry and the involved firms are often not competing (Hiete et al., 2012)) most likely influences the usefulness of the proposed strategies in different ways (Lewicki et al., 2006). As such, further exploratory case studies as well as survey studies are needed to fully understand the role and the development of trust for upfront investments in IS. Yet, our exploratory work may act as an umbrella framework and research agenda for further studies towards trust in IS.

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PAPER VI

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Improving waste quality in industrial symbiosis: insights on how to organize supplier integration

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Abstract
Reusing waste materials of other industries, a practice known as industrial symbiosis, attracts growing attention by industry. However, the waste materials are often of lower quality than the virgin materials they substitute. When production processes are intolerant for lower quality materials, production issues may occur. This paper sets out to explore how firms can improve the waste quality through supplier integration with the waste supplier. As suppliers have to learn new knowledge, the construct of absorptive capacity is used as an interpretive lens. An in-depth longitudinal exploratory case study approach is used to examine the involvement of different individuals and departments in the supplier integration activities in the context of the waste-based fuel supply chain of a global cement producer. Qualitative and quantitative data was gathered at both the buyer and the supplier. The data show that buyers can increase the absorptive capacity of the suppliers by aligning their own knowledge bases with the scope of the supplier integration. The increased absorptive capacity enables the suppliers to improve waste quality. Improving waste quality is an important capability of industrial symbiosis, especially when firms want to go beyond the low-hanging fruits and increase the effectiveness of their industrial symbiosis activities. The research concludes with theoretical and managerial insights into how firms can organize the supplier integration to improve waste quality in the context of industrial symbiosis.

Keywords: Supplier integration; industrial symbiosis; waste; process industry; supply chain, absorptive capacity.

1. Introduction

This research is inspired by a real-life case that the authors encountered during a research project at a cement manufacturer who is deeply engaged in industrial symbiosis – i.e. the practice of using waste and byproducts of other industries. After having captured the low-hanging fruits, the cement manufacturer aimed to increase the volume and the scope of their symbiotic activities. However, to maintain high final product quality and high operational efficiency in a production environment which is designed for the use of virgin materials, the waste products needed to conform with exacting quality standards. The cement manufacturer therefore engaged in supplier integration (SI): information exchange by means of reports, calls and e-mails as well as visits to each other. However, the SI did not lead to improved waste quality, even though supply chain literature suggests a positive relation between SI and supplier performance (Tan, 2001; Frohlich and Westbrook, 2001; Schoenherr and Swink, 2012) – e.g. improved waste quality. However, after changing the individuals involved in the SI, the SI led to improved waste quality.

The theory of absorptive capacity provides an interesting lens to explain how involving different individuals in the SI leads to improved waste quality. Absorptive capacity, which is defined as the ability to 'recognize the value of new, external information, assimilate it, and apply it to commercial ends' (Cohen and Levinthal, 1990, p. 129), succinctly captures the capabilities needed for knowledge transfers to improve waste quality. From here, three reasons might explain why SI may not achieve the set goals in the context of industrial symbiosis. First, *individuals* involved in the SI may fail to acquire and recognize the value of relevant information for improving waste quality. Second, *individuals* involved in the SI may fail to assimilate information on how to improve waste quality. Third, even if they acquire and assimilate relevant information, *individuals* involved in the SI may fail to apply this knowledge to improve waste quality (Cohen and Levinthal, 1990; Vanpoucke et al., 2014).

Yet, despite the large body of SI literature, the relationship between SI and who – at an individual or departmental level – is involved in SI remains largely unexplored and no clear-cut managerial implications have emerged (Wong et al., 2015). The research contributes to literature in the following ways. First, although absorptive capacity has been studied in buyer-supplier relationships in the manufacturing sector (Nagati and Rebolledo, 2012; Rojo et al., 2018; Zhang et al., 2018), contextual factors have so far been neglected and benefit from inclusion (Lane et al., 2006). Second, the insights of this study help firms in industrial symbiosis to align waste quality with production requirements, thereby contributing to progressing towards cleaner production (Gibbs and Deutz, 2007; Meneghetti and Nardin, 2012).

The remainder of this paper starts with introducing the main concepts of SI, absorptive capacity and industrial symbiosis. Next the longitudinal case study methodology is presented followed by the findings. After discussing the findings, the paper concludes with the implications for literature and practitioners and the limitations as well as avenues for further research.

2. Literature review

Case descriptions of industrial symbiosis show that industrial symbiosis often takes place in the process industry – see for example the industrial symbiosis in Chamusca in Portugal (Costa and Ferrão, 2010), Rotterdam in The Netherlands (Baas and Boons, 2004), Ulsan in South in South Korea (Behera et al., 2012) and the National Industrial Symbiosis Programme in the United Kingdom (Mirata, 2004). The process industry is characterized by high internal manufacturing complexity – 'the level of detail and dynamic complexity found within the manufacturing facility's products, processing, and planning and control systems' (Bozarth et al., 2009, p. 80). The process industry's high internal manufacturing complexity arises from the difficulty of measuring where production inefficiencies occur due to 1) the interlinked processes with no or only limited intermediate storage and 2) the random variation happening in the highly interlinked processes such as temperature and pressure variances (King, 2009; Van Donk and Van Dam, 1996). The high internal manufacturing complexity may lead to a complex relationship between waste quality and operational parameters and may, subsequently, create ambiguity about what waste quality entails. Conveying complex information requires interactive SI approaches such as face-to-face meetings, rather than more vicarious and passive SI approaches like Electronic Data Interchange systems and the exchange of performance evaluations (Huber, 1991).

However, employing interactive SI approaches alone may not enable suppliers to learn and, therefore, to improve waste quality. To acquire and to not miss out on valuable knowledge, suppliers benefit from a high understanding of the buyer's processes and products because it creates awareness of the requirements for potential improvements (Bozarth et al., 2009; Setia and Patel, 2013; Zahra and George, 2002). A lack of knowledge about the buyer's processes and products may hinder the supplier in extracting the meaning of the exchanged knowledge (Zahra and George, 2002) and to improve the waste quality accordingly.

Previous research shows that the construct of absorptive capacity offers guidance on how a firm's ability to interpret and act upon new knowledge affects the effectiveness of knowledge exchanges (Volberda et al., 2010), see for example the studies of Minbaeva et al. (2003), Lane and Lubatkin (1998) and Nagati and Rebolledo (2012). The next sections elaborate on why and how the construct of absorptive capacity provides a promising lens to explore SI performance in terms of improving waste quality.

Absorptive capacity

Absorptive capacity is a firm-level construct which relies upon the individual units of knowledge available within the firm as well as the efforts expended by the firm and their employees to utilize this knowledge (Cohen and Levinthal, 1990). The individual units of knowledge refer to the employee's ability, their educational background and their job-related skills (Cohen and Levinthal, 1990; Minbaeva *et al*., 2003). Following Zahra and George (2002), efforts to enhance the absorptive capacity can address two separate but complementary dimensions. First, potential absorptive capacity (PAC) creates knowledge through *acquiring* and *assimilating* relevant knowledge. Second, realized absorptive capacity (RAC) utilizes PAC through *transforming* and *exploiting* knowledge. So, PAC precedes RAC (Zahra and George, 2002). Table 1 provides a description of the supplier's PAC and RAC in relation to SI aimed at improving waste quality.

Table 1. Dimensions of absorptive capacity of suppliers in relation to improving waste quality through SI (based on Malhotra et al. (2005), Setia and Patel (2013), Vanpoucke et al. (2014) and Zahra and George (2002))

Dimensions	Sub-dimensions	Relation to supplier improvement through SI
PAC – create knowledge	Acquire	The capacity of the supplier to identify and gather relevant knowledge via SI for improving waste quality.
	Assimilate	The capacity of the supplier to internalize and comprehend the acquired knowledge required for improving waste quality.
RAC – utilize knowledge	Transform	The capacity of the supplier to combine existing knowledge with the newly created knowledge to identify opportunities to improve waste quality.
	Exploit	The capacity of the supplier to leverage existing competencies and to create new competencies to improve waste quality.

The unit of analysis of the construct of absorptive capacity has evolved over time. In their seminal paper, Cohen and Levinthal (1990) view absorptive capacity as a firm-level construct by arguing that absorptive capacity is an ability which firms develop over time by accumulating a relevant knowledge base based on the knowledge of the employees. However, Lane and Lubatkin (1998) and Dyer and Singh (1998) propose a dyadic (relational) rather than a firm-level unit of analysis. They argue that absorptive capacity in terms of acquiring new knowledge is determined by the relative relationship between the knowledge bases of the involved firms – the student firm (typically the supplier) and the teacher firm (typically the buyer). The overlap between the knowledge bases of the student firm and the teacher firm, together with interaction routines such as SI, largely determines the absorptive capacity of the student firm (Dyer and Singh, 1998; Lane and Lubatkin, 1998). Hence, a firm's absorptive capacity may differ depending on the firm they are collaborating with; when the SI takes place between a buyer and a supplier with overlapping knowledge bases, the SI will be more efficient.

Aligning the relative relationship of knowledge bases in the context of industrial symbiosis and high internal manufacturing complexity

As mentioned, SI in the context of industrial symbiosis in the process industry is often characterized by high internal manufacturing complexity. However, cognitive decision-making literature distinguishes between objective and perceived complexity (Campbell, 1988). *Perceived* internal manufacturing complexity is *not* a linear function of the complexity found in a facility's products, processing and planning and control systems (Manuj and Sahin, 2011; Robinson and Swink, 1994; Swink and Robinson, 1997). Instead, the knowledge of individuals may lead to low perceived complexity in cases of high objective complexity, i.e. what is perceived as complex by one person may not be perceived as complex by another person (Manuj and Sahin, 2011). Therefore, SI in a context with high objective complexity, such as industrial symbiosis in the process industry, may benefit from aligning the knowledge bases of individuals and departments with the scope of the SI as individuals with relevant knowledge bases may perceive the complexity as lower (Wong et al., 2015).

In fact, employees and departments within the same firm may have different knowledge bases (Galbraith, 1973; Swink and Schoenherr, 2014). For example, purchasing managers may have limited knowledge about the impact of waste on production processes. Moreover, the bounded rationality of individuals may keep them from obtaining knowledge about all relevant aspects (Simon, 1991). The buyer's procurement and the supplier's sales department may therefore perceive operational knowledge about the impact of waste on production as highly complex due to their bounded rationality and limited operational knowledge. Knowledge about manufacturing processes and products arguably resides within the operations departments, which may lower the perceived internal manufacturing complexity in these departments. So, SI aimed at improving waste quality may benefit from involving operations departments at both the buyer and the supplier. When the knowledge bases of the individuals and/or departments are aligned with the scope of the SI, we coin the SI as 'aligned SI'; opposed to 'misaligned SI' where the involved knowledge bases of the individuals and/or departments are not aligned with the scope of the SI. Figure 1 illustrates this.

		Supplier	
		Involved individuals / departments possess relevant knowledge about the impact of waste on production	Involved individuals / departments don’t possess relevant knowledge about the impact of waste on production
Buyer	Involved individuals / departments possess relevant knowledge about the impact of waste on production	A - Aligned SI	B - Misaligned SI
	Involved individuals / departments don’t possess relevant knowledge about the impact of waste on production	C - Misaligned SI	D - Misaligned SI

Figure 1. *Aligned and misaligned SI*

Note, aligned SI does not necessarily lead to the involvement of operations managers. Purchasing managers, for example, can still engage in aligned SI when their knowledge about operations is sufficient for the SI. Moreover, sometimes odd relationships can facilitate new insights and angles to a problem which individuals with similar outsets do not identify. Aligned SI may therefore not result in improved performance. In addition, aligning the SI alone may not be enough to improve waste quality. Other conditions may impact the SI as well such as power imbalances, relationship management and the depth of the integration (Prosman et al., 2016).

Collectively, literature says little about *who* should be involved in SI under different business conditions, such as high internal manufacturing complexity. An exception is the body of research on cross-functional buyer-supplier teams in new-product development literature – see for example Petersen et al. (2005). In line with the research aim, by exploring a case where there is a shift from misaligned SI (quadrant C in Figure 1) to aligned SI in a context with high internal manufacturing complexity, this paper explores the following research question from an absorptive capacity lens: *how and why does misaligned and aligned SI enable suppliers to improve waste quality in the context of high internal manufacturing complexity?*

Methodology

To empirically explore the research question, this paper adopts an in-depth longitudinal single case study. A case study design is appropriate due to the heavy reliance on the ability of qualitative data to gain a holistic and in-depth understanding of the *how's* and *why's* of the cause and effect between the phenomena of aligned and misaligned SI, objective and perceived internal manufacturing complexity and absorptive capacity (Eisenhardt, 1989; Eisenhardt and Graebner, 2007; Yin, 2009; Voss et al., 2002). Moreover, the complex context of this study – i.e. high internal manufacturing complexity and the role of absorptive capacity – renders a case study approach particularly suitable (Stuart et al., 2002).

The longitudinal approach allows to explore the effect of the shift from misaligned SI to aligned SI on the absorptive capacity and the effect on waste quality whilst guarding against problems with retrospective data – e.g. not recalling important events and post-rationalization (Eisenhardt and Graebner, 2007). Furthermore, the active presence in observing the phenomena provides access to rich data denied by other approaches (Voss et al., 2002). In addition, a longitudinal approach reduces (but not necessarily removes) the risk of misjudging an event and exaggerating easily available data (Eisenhardt and Graebner, 2007).

Case introduction

The study is conducted in the context of industrial symbiosis in the cement industry, where ‘Cema’, a cement manufacturer, procures waste-based fuel from ‘Marp’, a material recovery plant. Cema is a large and globally operating cement manufacturer and the plant under investigation is among the largest and most complex cement plants in the world. Marp, despite being a medium-sized firm, is a key supplier of Cema since waste-based fuel is of strategic importance for Cema due to environmental pressure from outside and the large share of waste-based fuel delivered by Marp (>40%). Cema started to procure waste-based fuels at Marp after Marp was acquired in 2015 by the same holding company also owning Cema. Although Cema and Marp continued to operate as separate entities, both firms operating under the same holding, offers a suitable context to explore the research question as it reduces the impact of mitigating and moderating factors beyond the scope of the research such as a fear for greater dependence due to the asset specificity of the SI (Williamson, 1982) and power erosion due to increased information sharing (Kähkönen, 2014).

The shift from misaligned to aligned SI between Cema and Marp offers fertile ground to gain insights into the research question. Although seemingly a commodity, the use of waste-based fuel in the cement industry is subject to high objective internal manufacturing complexity, as it is difficult to measure the impact of waste-based fuel quality on cement output. The pyro processing nature of cement production leads to complex interactions depending on various operational parameters which determine the output rate and quality of the cement. Furthermore, Marp's waste-based fuel consists of a heterogenous mix of materials, typically containing plastic residues, paper waste, textiles and other inorganic wastes. As a result, the waste-based fuel has a complex impact on kiln performance (Prosman et al., 2017). In fact, a number of (engineering) studies show the objective internal manufacturing complexity of waste-based fuel usage in cement production, see for example Rodríguez et al., 2015 and Summerbell et al., 2016. Hence, except for some straightforward quality aspects such as energy content, moisture levels and ash content, defining and improving quality for waste-based fuels in the cement industry is subject to high objective internal manufacturing complexity. In line with the research objective, this paper focuses on the ambiguous waste quality requirements rather than the obvious ones such as energy content.

Data collection

To explore the research question and to understand the complex context, data was collected from multiple sources to capture a wide variety of perceptions and meanings (Jick, 1979; Yin, 2009). In doing so, this paper follows Pentland's (1999) and Pettigrew's (1990) approach on theory building as by progressing through two stages from collecting surface-level data towards collecting detailed data.

In the first stage – between January 2016 and September 2016 – the first author spent two to three days per week at Cema's operations and procurement departments as well as a total of five days at Marp's operations departments. Furthermore, the first author attended meetings regarding waste-based fuel quality between Cema and Marp and between Cema's operations and procurement departments. In addition, unstructured interviews were held with all employees involved in the SI (see table 2). Collecting this surface-level data allowed the researchers to become ultimately familiar with the case and to understand the internal manufacturing complexity deriving from the use of waste-based fuel.

In the second stage, the obtained insights were used to conduct semi-structured interviews with employees from both Cema and Marp. The interviewees were selected based on their expertise and involvement in the SI (see table 2). To facilitate data comparison between misaligned and aligned SI, the interview protocol consisted of broadly defined themes with open-ended questions where the interviewee was probed to come up with detailed responses (Voss et al., 2002; Yin, 2009). The questions focused on the content of the SI, the role of the different dimensions of absorptive capacity and the effect on improving waste-based fuel quality. The semi-structured interviews lasted on average about one hour and were recorded and transcribed verbatim. In addition, written communication such as e-mails and documented correspondence in SAP rendered additional insights in the performance of both types of SI. Furthermore, hour-by-hour production data was collected from Cema's production processes to assess the improvements of ambiguous waste-based fuel quality requirements. This data was used to estimate the effect of waste-based fuel on production capacity (poor waste-based fuel quality reduces production capacity) whilst controlling for non-waste-based fuel related factors – see data analysis. In addition, data on production downtime related to waste-based fuels of Marp was collected for the periods before SI, during misaligned SI and during aligned SI. The collection of multiple and supplemental data increased the construct validity of this study (Voss et al., 2002; Yin, 2009).

Table 2. *Overview of interviewees*

Firm	*Interviewee*	*Unstructured interviews**	*Semi-structured interviews***	*Interviewee's relation to misaligned SI*	*Interviewee's relation to aligned SI*
Cema	Operations manager A	14	2	Communicate quality data to Cema's procurement	Communicate quality data to Marp's operations
	Operations manager B	5	1	""	""
	Purchaser	5	1	Acquiring quality data from operations and communicate this to Marp's operations	N/A
	Category manager	8	0	""	""
	Operational excellence manager	6	2	Supporting Marp in improving quality	Supporting Marp in improving quality
	Supply chain manager	5	1	Responsible for overall relationship	Responsible for overall relationship
	Strategic sourcing manager	3	1	""	""
Marp	CEO	4	1	Responsible for overall relationship	Responsible for overall relationship
	Operations manager A	6	2	Acquiring quality data from Cema's procurement and assimilate, transform and exploit this data	Acquiring quality data from Cema's operations and assimilate, transform and exploit this data
	Operations manager B	3	2	""	""
Total		59	13		

* Notes were taken
** Interviews are recorded and transcribed verbatim

Data analysis

Data was analyzed through a first- and second-order analysis. During the first-order analysis, statements as expressed by the employees involved in the SI in interviews, e-mails and correspondence documentation in SAP were coded (Gioia et al., 1994; Gioia and Chittipeddi, 1991). The codes related to concepts that clearly related to the research question 'how and why aligned and misaligned SI enables suppliers to improve ambiguous input quality in the context of high objective internal manufacturing complexity?' and the absorptive capacity lens. For example, "*we had limited knowledge about what was needed*" was coded as 'lack of exploitative capacity' and the quote from an interview after the shift to aligned SI "*it was a mess, but now we know where the targets are, where the KPIs are*" was coded as 'improved acquiring capacity'.

During the second-order analysis, the outcomes of the first-order analysis were used to search for an explanatory framework for the research question (Gioia et al., 1994; Gioia and Chittipeddi, 1991). The aim was to identify connections between misaligned and aligned SI and the effect on the different dimensions of absorptive capacity of Marp to improve ambiguous waste-based fuel quality. During this analysis, a recursive and iterative approach was balanced with early structure by linking the outcomes of the first-order analysis to constructs of the existing theory of absorptive capacity – e.g. acquiring and assimilating relevant information enables knowledge creation. Furthermore, production data was analyzed to test the effect of the improvements of ambiguous waste-based fuel quality on the output rate of production. To do so, the collected production data was divided into three groups: 'before SI', 'misaligned SI' and 'aligned SI'. To isolate the effect of waste-based fuels from Marp, days where the output rate was affected by non-waste-based fuel related issues (e.g. induced draft fan's speed, pressure drops, defects) was controlled for. Moreover, also periods where fossil fuels or waste-based fuels from other suppliers were used was controlled for. Furthermore, data from the first month after the implementation of misaligned and aligned SI was discarded to allow for an implementation period (the implemented improvements did not require significant changes) and the delays due to the shipping time of waste-based fuel. For the remaining data, the effect of waste-based fuel on the hourly output rate of production was tested by conducting a one-way analysis of variance (ANOVA) with post-hoc multiple comparison tests (Tukey) for the periods 'before SI', 'during misaligned SI' and 'during aligned SI'. Prior to the ANOVA, the data analysis tested for outliers, normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test for homogeneity of variances). As none of the assumptions of ANOVA were violated, the data analysis could proceed with the ANOVA test (Hair et al., 2009). The production figures are indexed for confidentiality reasons.

Next, peer debriefing – i.e. engaging researchers which are not involved in the research – to discuss emerging connections in the data was used. Moreover, preliminary versions of the findings were presented at Cema and Marp to discuss the interpretations and the explanatory framework. These discussions proved helpful in both finetuning the insights and in assessing the internal validity of the findings. In addition, throughout the data analysis process, NVivo was used to manage the data, to facilitate an overview of the codes and the chain of evidence, thereby increasing the reliability and validity of the findings (Yin, 2009). All statistical tests were carried out in R.

Findings

This section describes the misaligned and aligned SI between the buyer – Cema – and the supplier – Marp. For both types of SI, this section describes how SI took place, how SI affected Marp's absorptive capacity and Marp's ability to improve. Table 3 – at the end of this section – provides a quantitative perspective on the effect of misaligned SI and aligned SI on waste-based fuel quality based on production data.

Misaligned SI

In early 2016, Cema and Marp embarked on SI to improve waste-based fuel quality as waste-based fuel caused several issues at production. The SI took place through phone calls, written communication and the exchange of fuel specifications and fuel analysis reports between Cema's procurement department and Marp's operations departments. Furthermore, Cema's procurement representatives and Marp's CEO and operations managers visited each other to discuss how to improve waste-based fuel quality. Cema's operations department provided Cema's procurement representatives with access to accurate and relevant information. However, the SI did not render the desired result as the limited knowledge of Cema's purchase managers limited the absorptive capacity of Marp's operations managers. The following paragraphs present the findings in more detail.

The knowledge base of Cema's procurement department was misaligned with the scope of the SI – i.e. improving the quality of alternative fuel. Cema's procurement department acquired relevant knowledge from the operations department in the form of quality reports and face-to-face meetings in which operations managers explain how waste-based fuel quality affects cement production. However, despite the access to knowledge, Cema's procurement department struggled to understand waste-based fuel quality requirements and the impact on production. As Cema's operation manager (A) explains: "*it is difficult for them [Cema's procurement department] to understand the issues that it [the poor quality of certain aspects of the alternative fuel] can give us*". Similarly, but from a procurement perspective, Cema's supply chain manager points out: "*when they [Cema's operation managers] start to talk, I am directly out, it's too technical*". The low understanding results in ambiguity at Cema's procurement department about what alternative fuel quality entails. As Cema's purchaser mentions: "*we don't know what to measure*". Hence, the SI between Cema and Marp was misaligned due to the lack of knowledge at Cema's procurement department (see quadrant C of Figure 1 in the literature review).

The limited knowledge of Cema's purchasing department limited Marp's acquiring capacity and therefore limited Marp's PAC. Due to the poor understanding of waste-based fuel requirements in Cema's purchasing department, misaligned SI between Cema's procurement department and Marp's operations department did not contain relevant information. Operations manager A from Marp explains: "*They [Cema's procurement department] tell us [Marp's operations managers and Marp's CEO] that there is a problem with the quality, but there would not be any clarity towards what the problem is. They will just say there is a problem*". Documented correspondence between Cema and Marp confirms this: during the period of misaligned SI, quality issues are mentioned in vague terms in supplier correspondence (e.g. *"waste-based fuel caused problems with dust filters"* – SAP notification, October 2016). So, Cema's poor teaching skills led to misaligned SI and did not enhance the PAC, in particular the acquiring capacity, of Marp's operations managers.

The low PAC of Marp's operations managers limited them to improve waste-based fuel quality. Operations manager A from Marp explains: "*There is no real clarity towards what the problem is. They [Cema's procurement department] will just say there is a problem, which makes it hard to resolve the issue, when you do not know what you are trying to fix*". Likewise, operations manager B from Marp stresses that the limited amount of information reaching Marp's operations managers limits Marp from assimilating how to improve the quality of the alternative fuel:

> "*we don't know what is important to them. A lot of the information coming into the company, it is information with little understanding … there is very little understanding of how their [Cema's] processes operate … So, we cannot improve our process. And we also can't measure it when we don't know what is important… if they are not saying you need to be given it a little bit more of this, you need to do that, we are lost. We don't know what to do*"

The supplier correspondence in Cema's SAP system shows that Marp's response to vague improvement requests does not mention specific actions and typically resembles a '*we continuously try to improve the SRF [waste-based fuel]*' (response to aforementioned issue with the dust filters on October 2016). So, the low acquiring capability of Marp's operations managers limited their PAC and prevented them from improving waste-based fuel quality. Production data confirmed that waste quality did not improve, as such verifying the low performance of the SI, see table 3.

Aligned SI

In the summer of 2016, Cema directly engaged their operations department in the SI. Similar to the misaligned SI, the SI still took place through face-to-face meetings, phone calls, written communication and the exchange of quality documents and fuel analysis reports.

The involvement of Cema's operations managers led to aligned SI. First, Cema's operations department possessed knowledge about the scope of the SI – i.e. the quality of waste-based fuels. Furthermore, Marp's operations managers displayed a high understanding of Cema's processes when talking to Cema's operations managers: "*they [Marp's operations managers] understand what to do*" (Operations manager B, Cema). In addition, both Cema's and Marp's operations managers mentioned that they 'speak the same language' as they both have technical backgrounds. Hence, the new SI was aligned as the knowledge bases of both Cema's and Marp's operations managers were aligned with the scope of the SI.

The aligned SI between Marp's and Cema's operational functions increased the PAC of Marp's operations managers as it allowed them to acquire relevant information. As explained by operation manager A from Marp: "*it is good to see how the material is handled and used... we start to get a better understanding of what the issues are*". Furthermore, whereas the misaligned SI left Marp's operations managers in doubt about why and what to improve, the aligned SI clarified previously unclear communication: "*when you actually speak to them [Cema's operations managers] face-to-face or on the telephone, it is like 'no, no this is not what I meant, what I meant was…'*" (Operations manager B, Marp). So, aligned SI contributed to the PAC of Marp's operations managers by creating knowledge about what alternative fuel quality entails.

The increased PAC of Marp's operations managers allowed them to transform this knowledge by identifying how they can improve their processes and how they can exploit this by adapting their processes to improve waste-based fuel quality. Operations manager A from Marp explains: "*we [Marp's and Cema's operations functions] were drawing out the supply chain and we were looking at what influences the material at each stage of the supply chain. And that was when it became apparent, when we handle material on site, by our current practices at the time, how the quality of the material was affected*". So, due to aligned SI, Marp's operations managers were able to transform information into improvement opportunities. Marp's operations managers subsequently exploited the new knowledge to improve the quality of the waste-based fuel. Cema's operations managers confirm the improvements: "*the fuel of [Marp] does not create any problems anymore*" (operations manager B, Cema). Production data confirms the positive impact of the improved alternative fuel quality on production capacity (see Table 3).

The results in Table 3 indicate that unaligned SI did not have a positive impact on production capacity in the case of low waste quality in the context of high internal manufacturing complexity. Aligned SI, however, led to a significant improvement of production capacity in the same context: a 1.11% increase compared to the period before SI and a 1.24% increase compared to the period with unaligned SI. Such an increase is relatively large in cement production. In the case of Cema, where demand exceeds production capacity, the extra production capacity translates into significant profit gains. Furthermore, the kiln downtime related to waste-based fuel dropped with 44% after aligned SI – as such further increasing production capacity.

Table 3. *Analysis of variance with Tukey post-hoc tests for the hourly indexed production figures for the periods before SI, with unaligned SI and aligned SI**

	Before SI (N = 1177)	**Misaligned SI (N = 2110)**	**Aligned SI (N = 1632)**	**F. (Sig.)**
Mean (std. deviation)	100 (4.64)	99.87 (4.16)	101.11 (5.25)	35.791 ($p < 0,0001$)
Mean difference before SI (Sig.)**	-	0.13 ($p \approx 0,722$)	1.11 ($p < 0,001$)	
Mean difference misaligned SI (Sig.)**	-	-	1.24 ($p < 0,001$)	

* The period before SI equals 100.
** Tukey multiple comparison, 1-tail test.

In addition, in the studied case, aligned SI led to creating new knowledge about waste-based fuel quality beyond the knowledge creation originally set out for. Discussions between the operations managers of both firms as well as site visits created additional knowledge about waste-based fuel quality. For example, it was identified that ashes and alumina from certain wastes could be used for cement production, depending on their properties such as the chemical composition, density and stability. Having this information allowed Marp to reduce cost by eliminating redundant process steps and increase income by processing more types of waste.

Discussion

Literature suggests that absorptive capacity is determined by the relative relationship between the knowledge bases of the buyer and the supplier (Lane and Lubatkin, 1998). Therefore, in SI, the relative relationship between the buyer's and the supplier's knowledge base matters. The findings of this study suggest that firms can increase absorptive capacity by proactively involving (and excluding) certain knowledge bases from SI. In line with the aim of this paper, this section discusses the findings in more detail by using the construct of absorptive capacity and linking it to SI performance in the context of high internal manufacturing complexity.

The effect of absorptive capacity on SI performance

As the SI centered around technical and ambiguous aspects of waste-based fuel, Cema's knowledge base was initially misaligned with the scope of the SI (quadrant C in Figure 1 in the literature review). The misaligned knowledge base of the buyer led to poor acquiring capabilities of the supplier: Cema could not provide Marp with the relevant knowledge about product quality requirements. On the contrary, in the situation with aligned SI, Marp was able to acquire relevant knowledge from Cema. As such, in line with the work of Lane and Lubatkin (1998), the alignment of knowledge bases allowed Marp to obtain insights into how to improve waste-based fuel quality. Therefore, the first proposition is:

P1. Misalignment between the knowledge base of the buyer and the scope of the SI reduces the acquiring capability and thereby the absorptive capacity of the supplier.

Furthermore, the shift from misaligned SI to aligned SI suggest that firms can proactively align their knowledge bases with the scope of the SI. Hence, when firms design the SI, they should consider which knowledge bases to involve. Prudent decisions, where knowledge bases of the buyer and the supplier are aligned with the scope of the SI will enable higher SI performance due to the increased absorptive capacity of the supplier. Hence, buyers can proactively improve the suppliers' absorptive capacity by providing better knowledge to the supplier. This finding extends previous research on developing supplier integration capabilities – see for example Vanpoucke et al. (2014). Hence:

P2. Buyers and suppliers can proactively align their knowledge bases by involving individuals and departments with knowledge relevant to the SI to increase the absorptive capacity of the supplier.

This proposition further extends Lane and Lubatkin's (1998) dyadic view on absorptive capacity as this paper's findings suggest that absorptive capacity is determined by the relative relationship of the *involved* knowledge bases rather than the general knowledge base of the firm. This observation is congruent with amongst others Galbraith (1973) and Swink and Schoenherr (2014) who propose that firms may have multiple knowledge bases (e.g. logistics, operations) rather than a singular knowledge base (e.g. industry related).

Implications for theory and practice of supplier integration in the context of industrial symbiosis

The outcomes of this study contribute to the field of SI and industrial symbiosis and several managerial implications can be gleaned. While literature increasingly addresses how firms can deal with complexity in their supply chain (Manuj and Sahin, 2011) and while research indicates that SI is particularly useful in complex contexts (Gimenez et al., 2012), how firms should organize the SI in a complex context remains unclear (Van der Vaart and Van Donk, 2008; Van der Vaart et al., 2012).

However, the context of this study – industrial symbiosis – is often characterized by high internal manufacturing complexity since introducing waste often has a complex impact on production systems. This is especially the case when firms aim to go beyond the low-hanging fruits and where waste materials need to be optimized in accordance with the receiving process.

Following the logic of absorptive capacity, the findings presented in this paper suggest that firms can proactively align their knowledge bases with the scope of the SI in order to increase the supplier's absorptive capacity. As such, this study provides insights into which individuals and departments to involve in SI in the context of industrial symbiosis. Hence, this study provides both theoretical and managerial insights into how firms can increase the performance of their symbiotic activities – an area which attracts increasing research attention (Ghisellini et al., 2015).

Conclusion

In this paper a longitudinal case study was conducted to explore the shift from misaligned to aligned SI in the context of a symbiotic supply chain in the cement industry. In particular, the research question: *how and why does misaligned and aligned SI enable suppliers to improve waste quality in the context of high internal manufacturing complexity?* was explored. Our empirical data suggests that aligned SI improves the conditions for the supplier to improve waste quality in a context with high internal manufacturing complexity. Misaligned SI, on the other hand, may form a barrier for suppliers to improve waste quality in a context of high internal manufacturing complexity. Absorptive capacity provides useful insight into how firms can move from misaligned SI to aligned SI, for example by changing the individuals involved in the SI – like the studied case of Cema. Note, however, that this research by no means intends to claim that changing the individuals in the SI in line with their knowledge is the only strategy to achieve aligned SI and improve waste quality. Other strategies may include educating individuals or creating boundary objects such as technical drawings, breakdown reports, machine-utilization reports, etc. to enhance the learning of the supplier (Carlile, 2002). Moreover, aligned SI may have some disadvantages compared to misaligned SI such as too much emphasis on waste quality due to the involvement of operations managers (rather than an overall cost emphasize). Also, the inclusion of different mindsets in misaligned SI might lead to new insights and angles to a problem. In addition, aligning the SI is only part of a bigger picture: poor relationships, power imbalances and other factors may also affect the end result: the effectiveness of the SI to improve waste and byproduct quality.

As a final reflection, this paper is not without limitations. The main limitation is the reliance on a single case. Although providing rich data, a single case study increases the risk of misjudgment of a single event and exaggerating easily available data (Voss et al., 2002). We tried to limit these biases though data triangulation of interview data, archival sources, production figures and presenting the results to the interviewees and stakeholders in the SI as a final check. Nevertheless, future research benefits from testing the propositions on larger samples. Furthermore, this paper only addressed one type of misaligned SI (quadrant C of figure 1 in the literature review). The other types of misaligned SI may require different solutions. Future research should therefore explore other types of misaligned SI. Absorptive capacity might provide a useful theoretical lens for such research.

Nevertheless, despite the limitations, this paper has made an important contribution to both literature and practice by enhancing the understanding of SI performance in terms of how and why SI performance is conditioned by absorptive capacity and how firms can increase SI performance.

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CONFERENCE ABSTRACT I

Sacchi, R. and Prosman, E.J, "A procedure to sidestep the lack of data for waste-based product systems", presented at the 23rd SETAC Europe LCA case studies symposium.

A procedure to sidestep the lack of data for waste-based product systems

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1. Introduction

With an increasing share of industries that rely on the use of waste material to subsitute the need for virgin resources, it is paramount that the CLCI modeling of the material supply identifies the correct waste treatment activity affected by the removal of available material from the market.

Waste-based product systems may perform very differently as the affected waste treatment technology at the margin changes [1]. Following Weidema, Frees, and Nielsen [2], the identification of marginal technologies requires time series on the market volumes and information on the different competing technologies.

Unfortunately, CLCI modeling information for waste products is not abundant in commercial CLCI databases. Often, when an indication on the affected waste treatment is provided, it is done regardless of the sourcing location or the market state for that material. This is caused by a lack of precise data on waste availability and an insufficient disaggregation between waste types in national statistical databases.

The next paragraphs suggest CLCA practitioners a three-step procedure to model the sourcing of waste material for which the available market data does not allow to clearly identify the marginal treatment activity. The overall idea relies on the use of information surrounding the raw material the waste product stems from, for which data is generally more accessible. The procedure is applied to the sourcing of fly ash, the volatile part of the coal combustion residues.

2. Method

2.1. Step 1: Solving the unknown on the offer side

As a first step, we characterize the different European markets for fly ash production. This is achieved by modelling the coal trade in an input-output table for several years (2009-2014), using United Nations' trade database COMTRADE (trade codes *27.01.11* and *27.01.12)* [3]. With the Leontief inverse, we can deduct the type and amount of coal consumed for each European country over time, where consumption = imports + production – exports (hence, no long-term storage). Knowing the origin of the coal supply for each market, we match it with the corresponding ash content found in the proximate analyses provided by the USGS world coal quality inventory database COALQUAL [4]. This is important as the ash content in coal can vary from 2 to 50% of its wet mass depending on its type and location. This lets us derive the slope of available volumes of fly ash for each country, assuming a 5% Loss On Ignition ratio (representative of European coal-fired power plants) and a fixed 90:10 split ratio between fly and bottom ash.

2.2. Step 2: Solving the unknown side of the demand

As a second step, we use the aggregated statistics on combustion ash treatment provided by EuroStat's *env_wasgt* database (European waste code *10.01*) [5]. The selected waste code provides the closest aggregate level data on a country level (although including other combustion ashes such as slags and bottom ash). Based on the data, we estimate the trend for the different treatment technologies for fly ash over time (2009-2014).

2.3. Step 3: Determining the marginal waste treatment activity

Once we characterized both ends of the market, we can identify the affected treatment technology following an increase in demand for fly ash in each country after the procedure presented by Weidema et al. [2]. On a market with declining volumes over time, the treatment activity affected by an increase in demand (or reduction in available amounts of material) is the activity that received less and less material to treat over time. Inversely, on a market with increasing volumes of available material, the affected treatment activity is the activity that has received increasing amounts of material over time.

3. Results and discussion

Figure 1 gives a graphical example of Step 1 with the supplying coal markets for The Netherlands in 2014, where half the coal came from Colombia with an average ash content of 6%, weight-basis. Figure 2 shows the fly ash volume trends for the European markets (on the left), as well as their respective affected treatment activity (on the right). The general view holds that fly ash becomes increasingly scarce in most European countries due to the progressive phasing-out of coal-fired power plants. An in-depth analysis of the results as well as talks with experts in the cement industry leads to think that less and less fly ash is landfilled as businesses compete for fly ash due to environmental and economic reasons. Fly ash usage particularly increases in the concrete industry as it offers an economically attractive way of complying with the market's environmental demands while substituting the need for Portland cement (fly ash has cementious properties), hence outcompeting other fly ash uses such as filling material or as a Portland clinker substitute. Figure 2 suggests that sourcing fly ash from specific locations might be done at the expense of other reuse activities. The options the affected activities have in order to compensate for the lack of fly ash need to be considered in the CLCI.

Figure 1: Solving the origins of coal for The Netherlands in 2014. Green circle: destination. Red circles: supply.

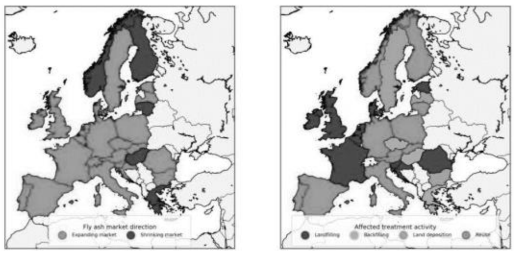

Figure 2: Left – The fly ash market trends. Right – The affected waste treatment activity.

4. Conclusions

Our work suggests an alternative procedure for modelling the supply of waste materials in CLCI when waste market data is lacking. A potential weakness of the procedure is the reliance on aggregated waste treatment data for ashes. Hence, expert views as well as access to Eurostat's microdata might be needed to verify the results in this case. Nevertheless, we believe that the proposed procedure helps to understand better the environmental consequences associated to waste supply. This contrasts with the generally adopted rules for attributional LCI where the use of residual materials is often considered free of any environmental burden.

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NEWSPAPER ARTICLE

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Grøn økonomi: Affald er en god forretning

Restaffald fra virksomheder kan være godt brændstof i industrien - og gavner både CO2-konto og pengepung.

Restaffald kan bruges som brændsel i produktionsvirksomheder. Men det kræver samarbejde mellem virksomhederne at finde frem til den bedste affaldskvalitet, hvis det skal være en god forretning, siger ph.d.-studerende Ernst-Jan Prosman. (Foto: Mogens Holmgaard © Holmgaardfoto.dk)

AF ANNE BOLLERSLEV
01. JUL. 2017 KL. 15.58

MAIL TWITTER FACEBOOK

Cirkulær økonomi er det nye sort indenfor det grønne område. Regeringen har sat fokus på, hvordan de danske virksomheder kan styrke væksten med grønne forretningsmodeller og bedre udnyttelse af ressourcerne.

Affald fra industrien er én af de ressourcer, virksomhederne kan blive bedre til at udnytte. Industriaffald kan fx erstatte de begrænsede fossile brændstoffer som kul og olie, der ellers bruges til produktion.

Hvordan det kan blive en god forretning, er Ernst-Jan Prosman, ph.d.-studerende ved Aalborg Universitet, godt i gang med at undersøge.

- De genbrugsvirksomheder, der leverer affald, skal lære at tænke på en anden måde. De skal have forståelse for den virksomhed, der skal bruge affaldet. For affaldsafbrænding kan påvirke produktionen på forskellige måder. Derfor er det også vigtigt, at det er virksomhedernes teknikere og ikke kun handelsfolkene, der arbejder sammen, siger Ernst-Jan Prosman.

CIRKULÆR ØKONOMI

Cirkulær økonomi handler om at genbruge og genanvende ressourcer til ny produktion.

Ifølge Ellen MacArthur Foundation kan en omstilling til cirkulær dansk økonomi frem mod 2035 reducere CO2-udledningen med 3-7 procent og halvere forbruget af ressourcer.

I starten af juni afleverede et særligt råd for cirkulær økonomi 27 anbefalinger til regeringen.

Billigere brændsel

Industriel symbiose, hvor virksomheder arbejder sammen om at udnytte industriaffald, er rammen for Ernst-Jan Prosmans studie, hvor han tager udgangspunkt i cementvirksomheden Aalborg Portland.

Cementproduktion er meget energikrævende, og derfor ønsker Portland at bruge mere biomasse til at brænde cementen. Det er nemlig billigere, og det nedsætter CO2-udledningen, så Portlands udgifter til CO2-kvoter bliver lavere.

GRØN INDUSTRISYMBIOSE

I en grøn industrisymbiose bliver affaldet fra én virksomhed brugt i en anden. Det kan være som brændsel eller som råmateriale.

Genanvendelsen fører til et lavere forbrug af ressourcer og udledning af CO_2.

Industrisymbiose kan foregå som direkte handel mellem virksomheder. Handlen med affald kan også foregå via genbrugsvirksomheder, der håndterer restaffald fra mange forskellige virksomheder.

Sidste år udgjorde alternative brændsler 45 procent af den mængde, fabrikken bruger til produktionen af grå cement.

LÆS OGSÅ: Fejl får Klimarådet til at skrue markant op for CO2-reduktionen

Affald fra udlandet

I Danmark bliver en stor mængde restaffald i dag brugt til varmeproduktion i forbrændingsanlæg. Aalborg Portland får derfor restaffald fra genbrugsvirksomheder i udlandet - blandt andet i Storbritannien - der ikke selv har kapacitet til at brænde affaldet.

Restaffaldet er den mængde, der er tilbage, når genanvendeligt materiale som plast, papir og metal er sorteret fra til genbrug.

- Hvis restaffaldet kan anvendes til forbrænding i Danmark, er det jo bedre for miljøet, siger Ernst-Jan Prosman.

De danske affaldsforbrændingsanlæg leverer omkring en femtedel af vores fjernevarme i private hjem. Men også i industrien kan affaldsvarme altså være en god forretning. Her et billede fra Amagerforbrændingen. (Foto: søren bidstrup © Scanpix)

Forædlet affald

Men alt restaffald kan ikke umiddelbart bruges til cementproduktion. Det må fx ikke indeholde pvc, som stopper brændeovnen til. Og er der for meget vand i affaldet, er brændværdien ikke særlig høj. Og så er det ikke længere end god forretning, selvom affaldet som udgangspunkt er et billigere brændstof.

AFFALD I DANMARK

Den seneste opgørelse over affald i Danmark viser, at industrien i 2015 producerede 1.157.000 tons affald, heraf blev 72 procent genanvendt og 18 procent gik til forbrænding.

Til sammenligning producerede de danske husstande 3.353.000 tons affald, hvoraf 46 procent blev genanvendt og 52 procent forbrændt.

I 2015 importerede Danmark 1.150.000 tons affald mod 797.000 tons i 2013. En stor del, 492.000 tons blev brugt til varmeproduktion i de danske forbrændingsanlæg. 40 procent af affaldet kom fra Storbritannien.

Kilde: Miljøstyrelsens affaldsstatistik 2015

- Der går en lang og kompleks proces forud for, at det affald, som bliver dannet ved én virksomhed, kan blive nyttiggjort af en anden. Det kræver et tæt samarbejde, og her hjælper jeg med at optimere leverandørens produktion med det formål at øge kvaliteten af det restprodukt, som efterfølgende købes og anvendes af Aalborg Portland, fortæller Ernst-Jan Prosman.

Udfordringen er her blandt andet, at salg af restaffald er et nyt område for de engelske genbrugsvirksomheder. De producerer ikke selv affaldet, og de har måske ikke detaljeret kendskab til, hvad det består af, og om det indeholder miljøskadelige stoffer.

De skal derfor lære, hvordan de bedst muligt analyserer og forarbejder restaffaldet, så det giver størst værdi for den danske cementproducent. Samtidig skal de kunne se værdien i at forbedre affaldskvaliteten.

- Genbrugsvirksomhederne skal forstå, at hvis de forædler affaldet, så kan de også afsætte mere til en bedre pris. Så for dem er der også et økonomisk incitament i det.

Ernst-Jan Prosman peger derfor på, at det er vigtigt, at virksomheder, der skal bruge industriaffald, ser på, hvordan de organiserer samarbejdet med de virksomheder, der skal levere affaldet.

SUMMARY

In the wake of unprecedented global economic expansion and a quickly increasing middle class, the current economic models jeopardize our future by causing resource depletion, excessive land use and global warming. To address this, concepts such as industrial symbiosis – where waste and byproducts of one industry are used as feedstock for another industry – are gaining traction. However, despite the growing attention and the concept's importance for our future, how to manage supply chain related issues in this context has received rather scarce attention. Yet, firms have to deal with low and varying quality of waste and byproducts, cross-industry collaborations and a lack of transparency in the upstream supply network.

Building on six studies and one conference abstract, this research presents supply chain capabilities for key domains in the context of industrial symbiosis in the process industry: 1) sourcing, 2) environmental supplier selection, 3) setting up new symbiotic exchanges and 4) managing supplier integration to improve waste and byproduct quality. The broad supply chain perspective helps managers and academics alike to understand the challenges and the solutions.

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